Jig-Shape Optimization of Quiet Supersonic Technology X-plane

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Overview

- Theoretical background (slides 4-10)

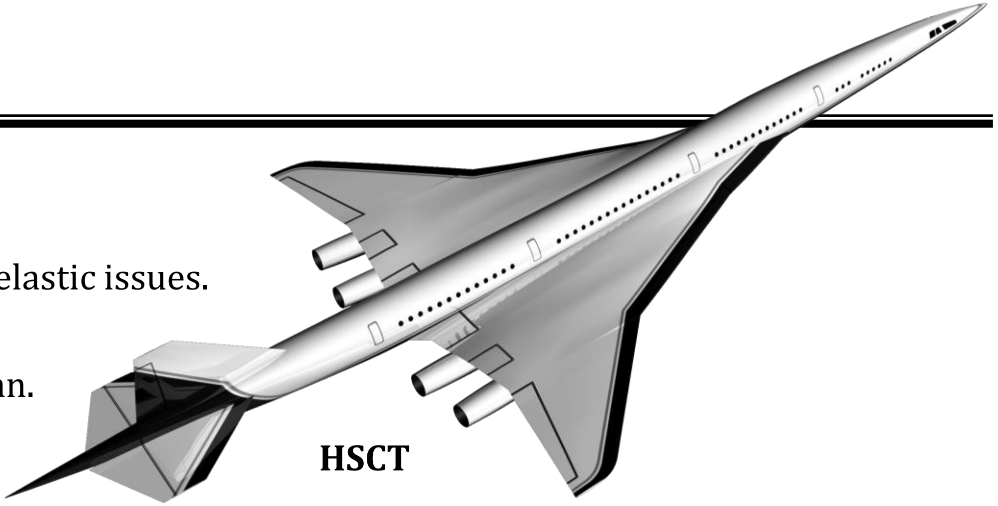
- Computational validation (slides 12-26)

- Conclusions (slide 27)

Theoretical background

Introduction

- Supersonic Commercial Transport Aircraft Design
  - Safety
    - Light weight airframe can cause strength, buckling, aeroelastic, and aeroservoelastic issues.
  - Sonic boom
    - Supersonic flight of "commercial transport" aircraft allowed only over the ocean.
    - Perceived Loudness in decibels
      - ✓ **NASA's N+2 goal: 75 PLdB**
      - ✓ Concorde: **104 PLdB**
      - ✓ High Speed Civil Transport (HSCT): **99 PLdB**
  - Fuel efficiency
    - Light weight airframe
    - Reduced drag
- Developing Quiet Supersonic Technology (QueSST) X-plane
  - Low Boom Flight Demonstrator (LBFD)
  - Lockheed Martin Skunk Works is the prime contractor for preliminary design.
  - **Loudness: 74 PLdB**
- Major Issue
  - Out-mold-line configuration of an aircraft is design for the desired aerodynamic performance. Assume rigid structure.
  - Flexibility of the structure changes the aerodynamic performance.
  - It has been reported that one degree of the tip twist of a LBFD wing and stabilator under the cruise flight condition can increase the sonic boom level by 0.2 PLdB and 1.3 PLdB, respectively.



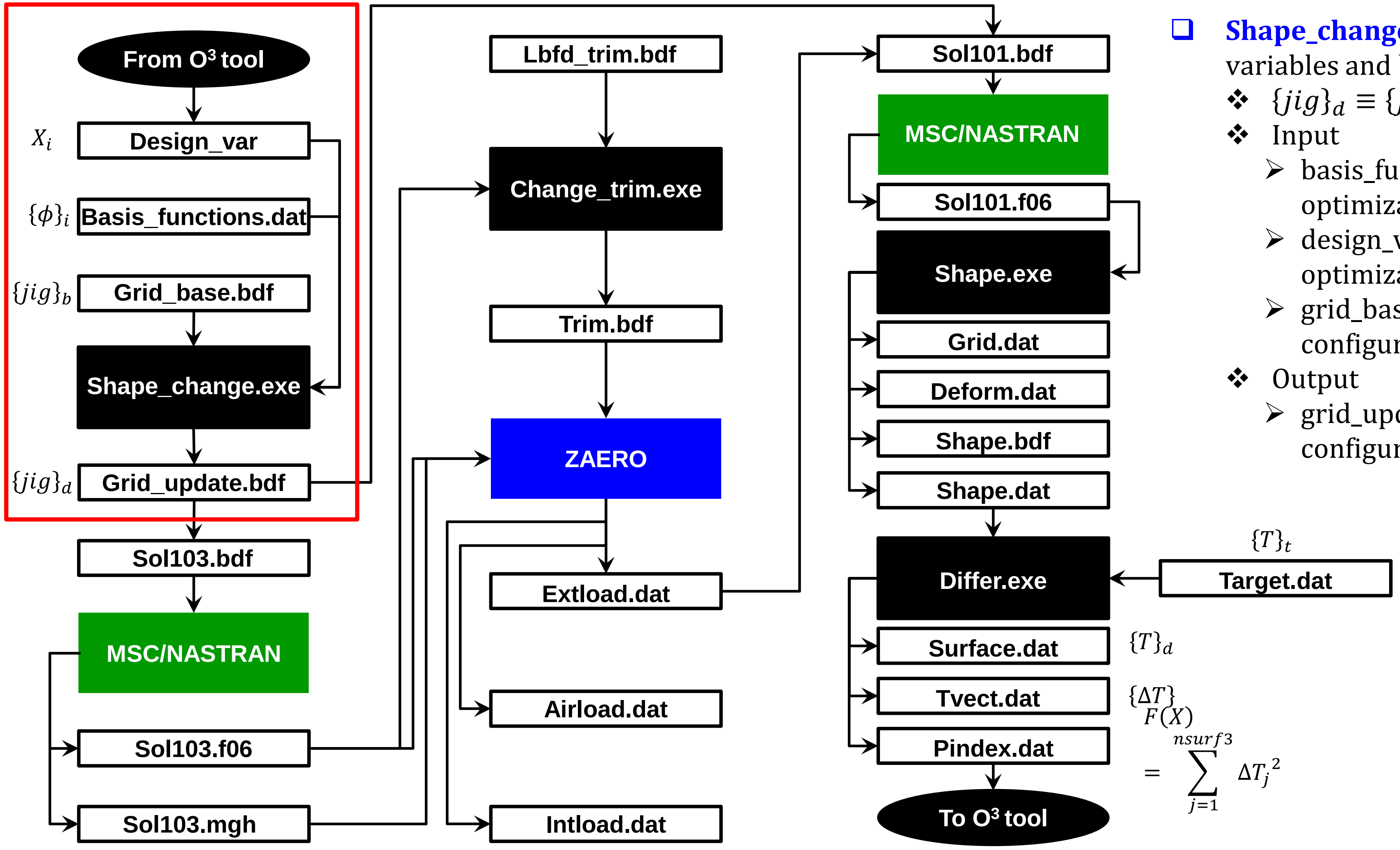
Jig-Shape Optimization Problem Statement

- Assume unconstrained Optimization
- Optimization Problem Statement
  - Find design variables: $\{X\} = \lfloor X_{1,} X_{2,} \ldots, X_{ndv} \rfloor^T$ which

$$minimize \left\{ F(X) = \sum_{j=1}^{nsurf3} \Delta T_j{}^2 \right\}$$

  - $\{\Delta T\} \equiv \{T\}_t - \{T\}_d$
  - $\{T\}_t$= target trim shape at surface GRIDs
    - Sonic boom level is computed based on target trim shape.
  - $\{T\}_d$= trim shape based on design jig shape
    - $\{jig\}_d \xRightarrow[trim\ analysis]{} \{T\}_d$
    - $\{jig\}_d \equiv \{jig\}_b + \{\Delta jig\}$
      - ✓ $\{jig\}_d$= design jig-shape
      - ✓ $\{jig\}_b$= baseline jig-shape
      - ✓ $\{\Delta jig\}$= jig-shape changes
    - $\{\Delta jig\} = [\mathbf{\Phi}]\{X\}$
      - ✓ X_i= i-th design variable
      - ✓ $[\mathbf{\Phi}] = [\{\phi\}_1 \{\phi\}_2 \ldots \{\phi\}_{ndv}]$
        - $\{\phi\}_i$ = i-th basis function
          - Eigen vector based on jig shape
          - Eigen vectors are normalized as Max deflection = 1 inch.

Update Jig-Shape Module: using shape_change.exe

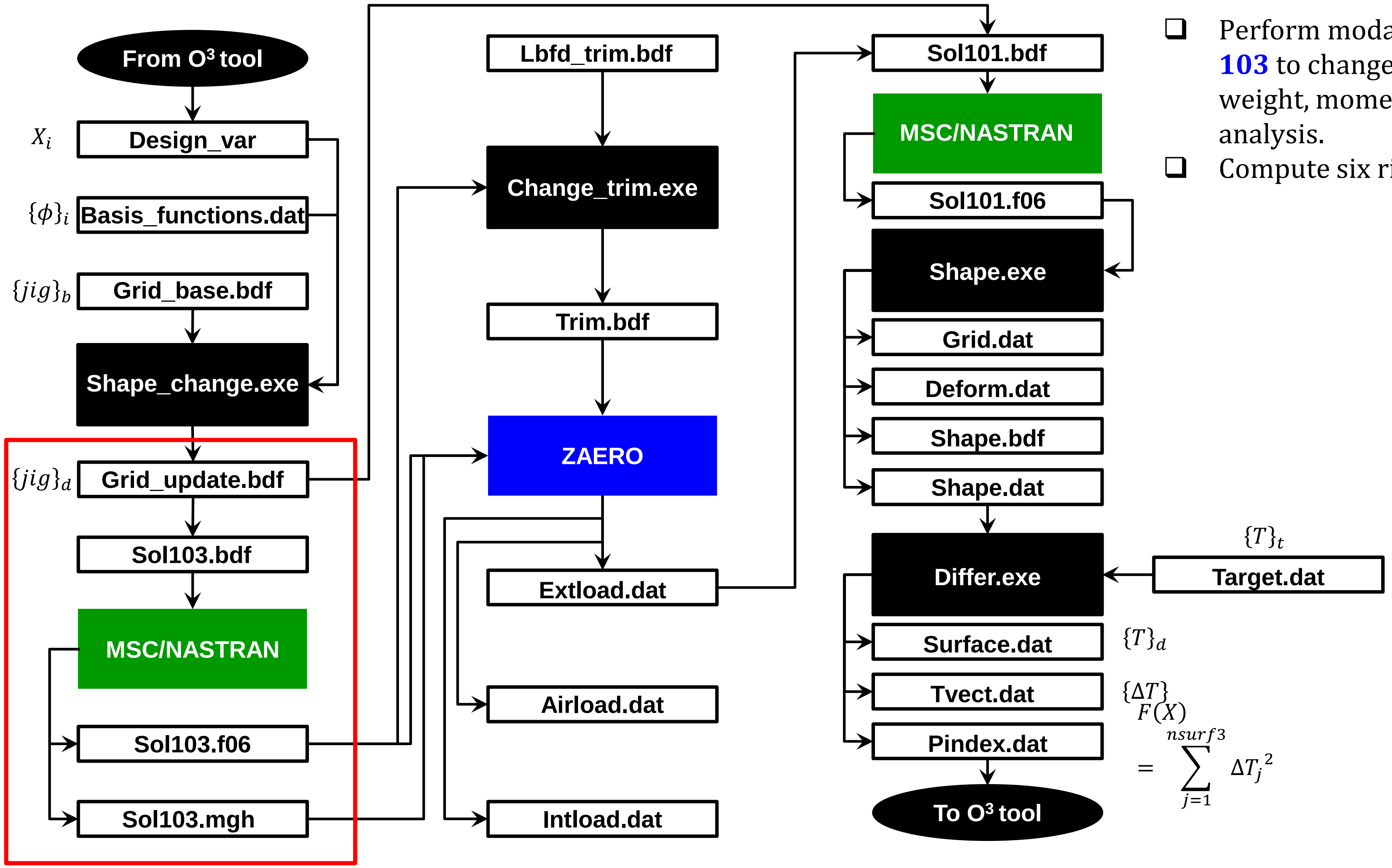


- **Shape_change.exe**: Change jig shape using design variables and basis functions.
  - $\{jig\}_d \equiv \{jig\}_b + [\mathbf{\Phi}]\{X\}$
  - Input
    - basis_functions.dat: basis functions for the shape optimization
    - design_var: design variables of the current optimization step
    - grid_base.bdf: GRID information of the baseline configuration (a template file)
  - Output
    - grid_update.bdf: GRID information of the updated configuration

Change jig shape using design variables & basis functions.

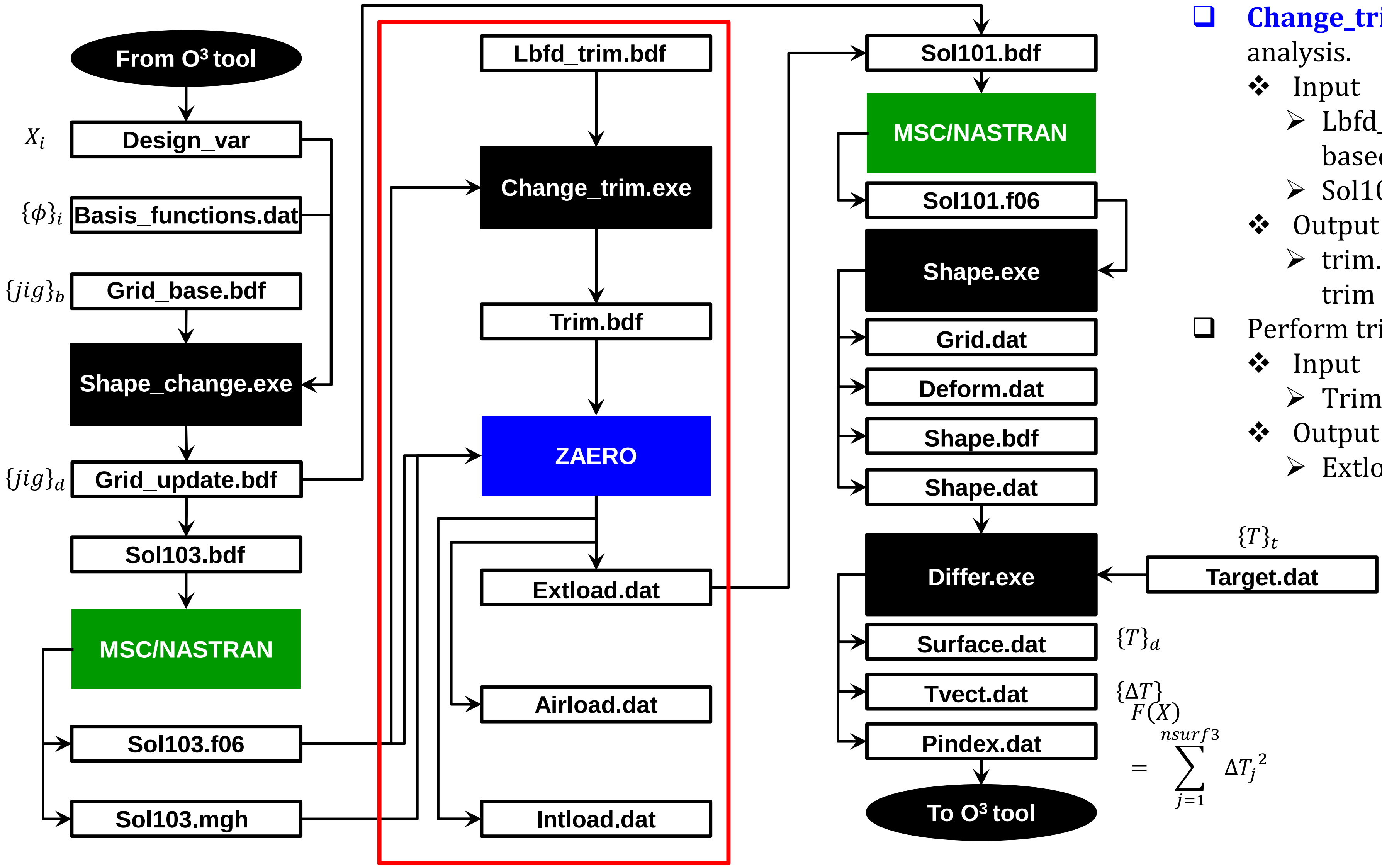
Modal Analysis Module: using MSC/NASTRAN solution 103

- Perform modal analysis using **MSC/NASTRAN solution 103** to change system mass matrix (MGH matrix), weight, moment of inertia, and CG location for trim analysis.
- Compute six rigid body modes.



Change mode shapes, weight, moment of inertia, & CG location for trim analysis.

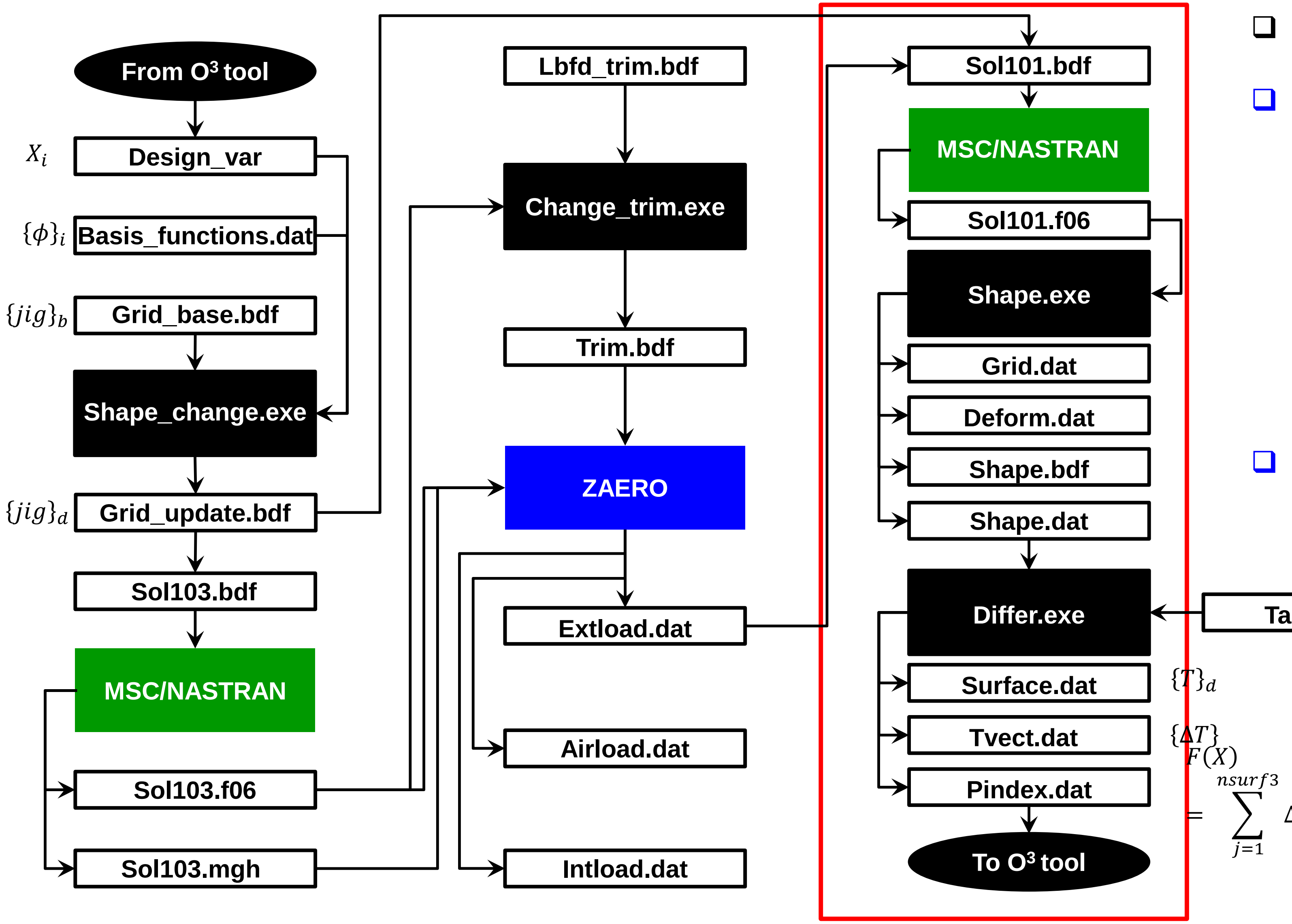
Trim Analysis Module: using ZAERO & change_trim.exe



- **Change_trim.exe**: Update input deck for ZAERO trim analysis.
  - Input
    - Lbfd_trim.bdf: template input file file for ZAERO based trim analysis
    - Sol103.f06: f06 file from MSC/NASTRAN
  - Output
    - trim.bdf: updated ZAERO input file to be used for trim analysis
- Perform trim analysis using **ZAERO**
  - Input
    - Trim.bdf
  - Output
    - Extload.dat: aerodynamic load + inertial load

Compute external load using ZAERO code.

Objective Function Module: using MSC/NASTRAN solution 101, shape.exe, & differ.exe

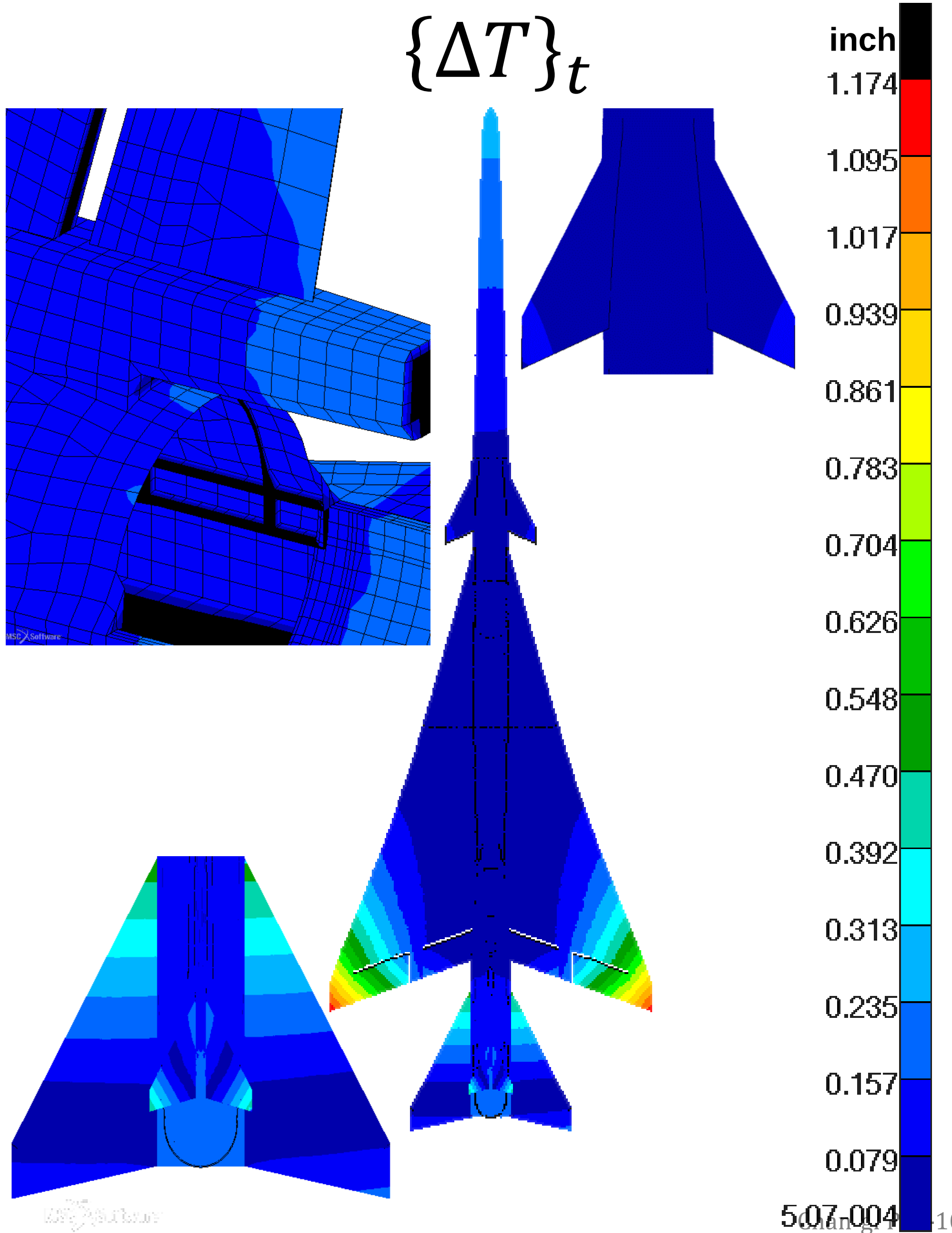


- **Perform static analysis** using inertia relief. (**MSC/NASTRAN sol. 101**)
- **Shape.exe**: read and write trim results.
  - Input
    - Trim.f06: MSC/NASTRAN output from sol. 101
  - Output
    - Grid.dat: GRID geometry information (@ all GRID)
    - Deform.dat: deformed shape (@ all GRID)
    - Shape.dat: GRID geom. + deformed shape (@ all GRID)
    - Shape.bdf: shape.dat in MSC/NASTRAN input deck format
- **Differ.exe**: compute performance index
  - Input
    - Shape.dat
    - $\{T\}$ Target.dat: $\{T\}_t$ @ surface GRID
  - Output
    - Pindex.dat: performance index for objective function; $F(X)$
    - Tvect.dat: $\{\Delta T\}$
    - Shape_diff.dis: $\{\Delta T\}$ @ surface GRID for MSC/PATRAN plotting
    - Surface.dat: shape.dat @ surface GRID; $\{T\}_d$

Compute trim deformation using MSC/NASTRAN solution 101 using inertia relief.

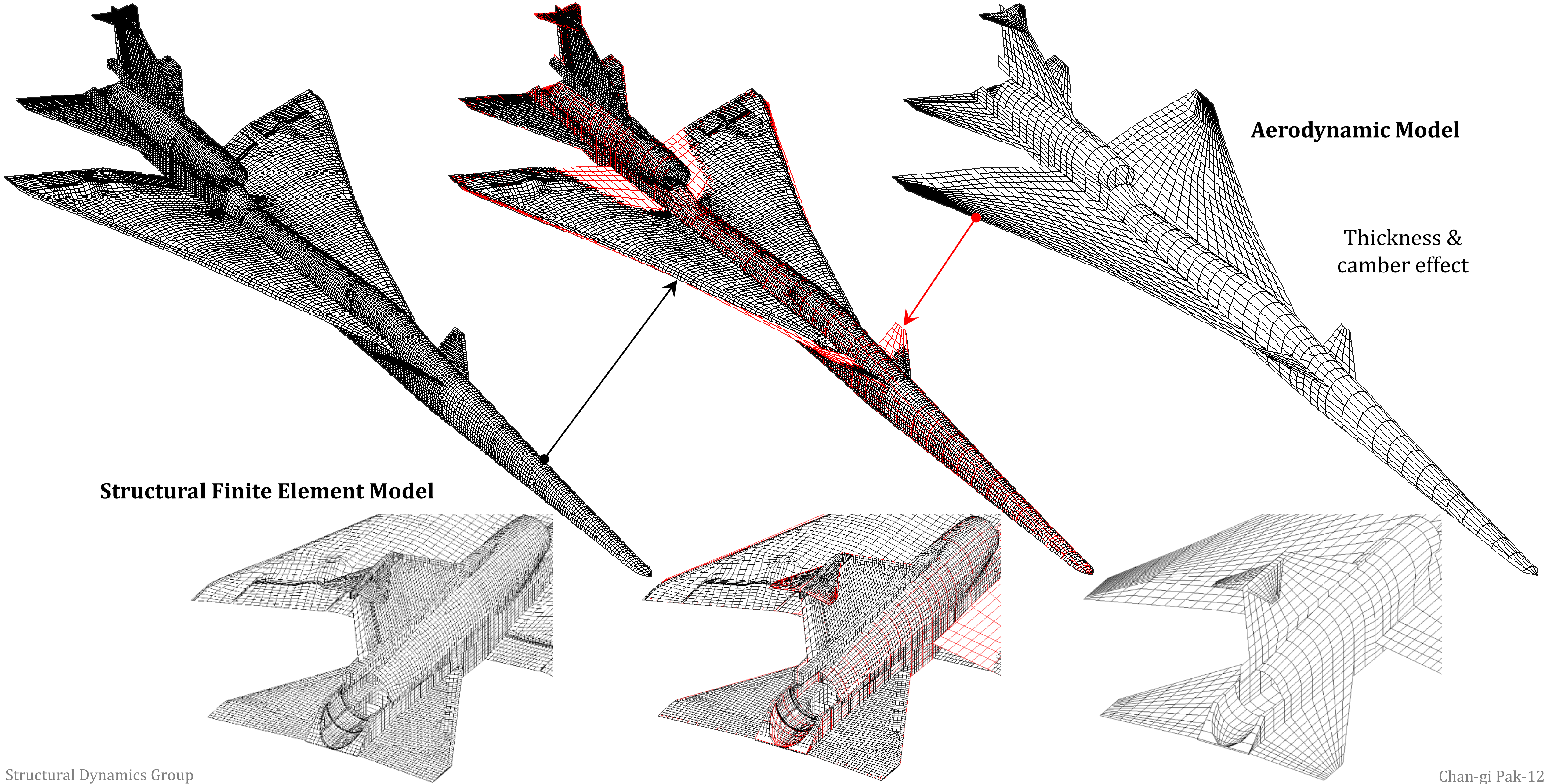
Compute Starting Design Variables: Using Least Squares Surface Fitting Technique

- $\{\Delta T\}_t \equiv \{T\}_t - \{T\}_b$
  - $\{T\}_t$= target trim shape at surface GRIDs
  - $\{T\}_b$= trim shape based on the baseline jig-shape
    - $\{jig\}_b \xrightarrow[\text{trim analysis}]{} \{T\}_b$
- Fitting $\{\Delta T\}_t$ surface using perturbed shapes $\{\Delta T\}_i, i = 1, 2, \ldots, ndv$
  - Perturb baseline jig-shape using basis functions $[\boldsymbol{\Phi}]$
    - $\{jig\}_d \equiv \{jig\}_b + [\boldsymbol{\Phi}]\{X\}$
    - Where, $\{\phi\}_i$= i-th basis function
    - $\{jig\}_b + \{\phi\}_i \xrightarrow[\text{trim analysis}]{} \{T\}_i$
    - $\{\Delta T\}_i \equiv \{T\}_i - \{T\}_b$ (i-th perturbed shape)
  - Define a matrix: $[\boldsymbol{\Psi}] = [\{\Delta T\}_1 \{\Delta T\}_2 \ldots \{\Delta T\}_{ndv}]$
- $[\boldsymbol{\Psi}]\{X\} = \{\Delta T\}_t$
  - $[\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}]\{X\} = [\boldsymbol{\Psi}]^T\{\Delta T\}_t$
  - $([\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}])^{-1}[\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}]\{X\} = ([\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}])^{-1}[\boldsymbol{\Psi}]^T\{\Delta T\}_t$
- Starting design variables: $\{X\} = ([\boldsymbol{\Psi}]^T[\boldsymbol{\Psi}])^{-1}[\boldsymbol{\Psi}]^T\{\Delta T\}_t$



Computational validation

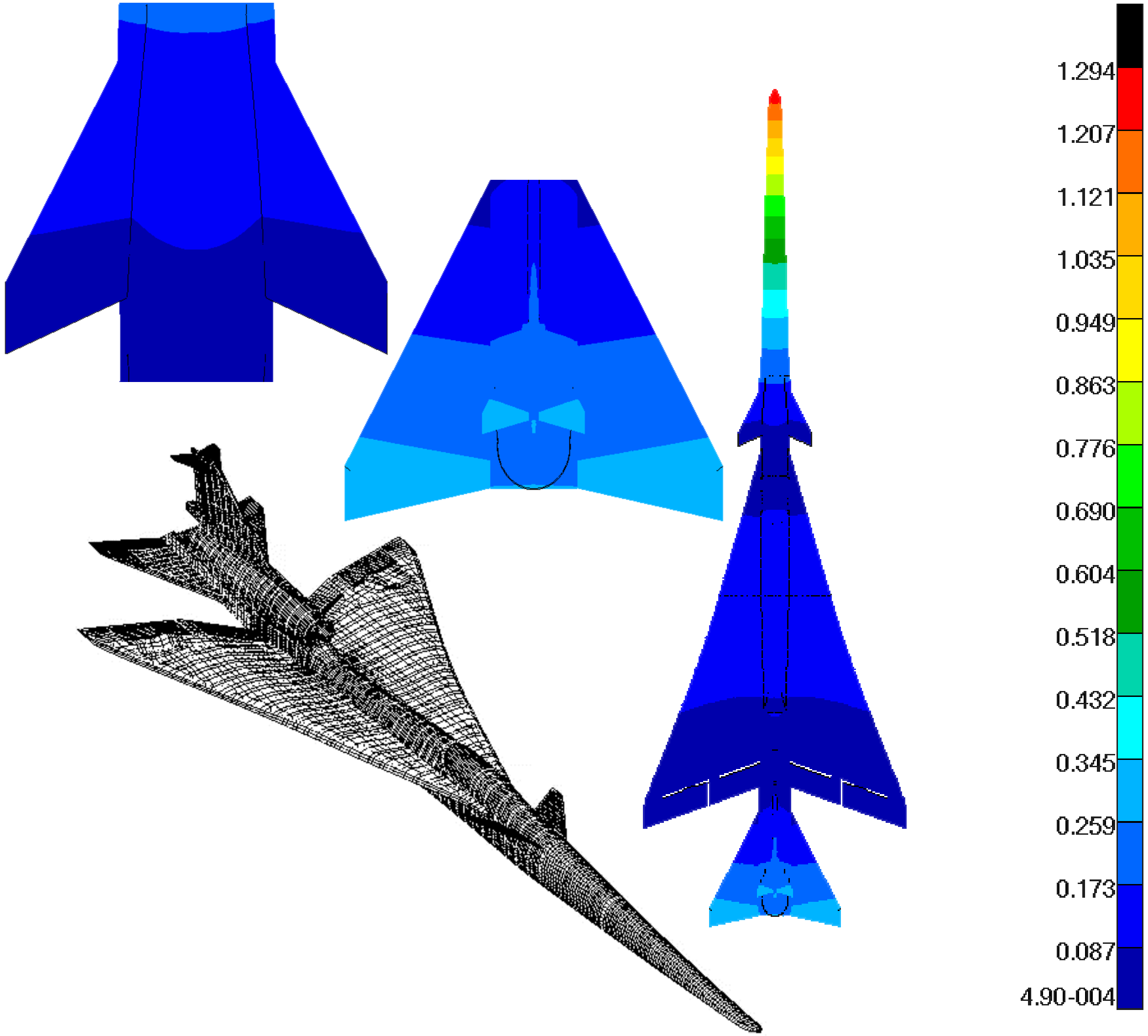
Structural Finite Element Model and Aerodynamic Model



Summary of Natural Frequencies (Baseline Configuration)

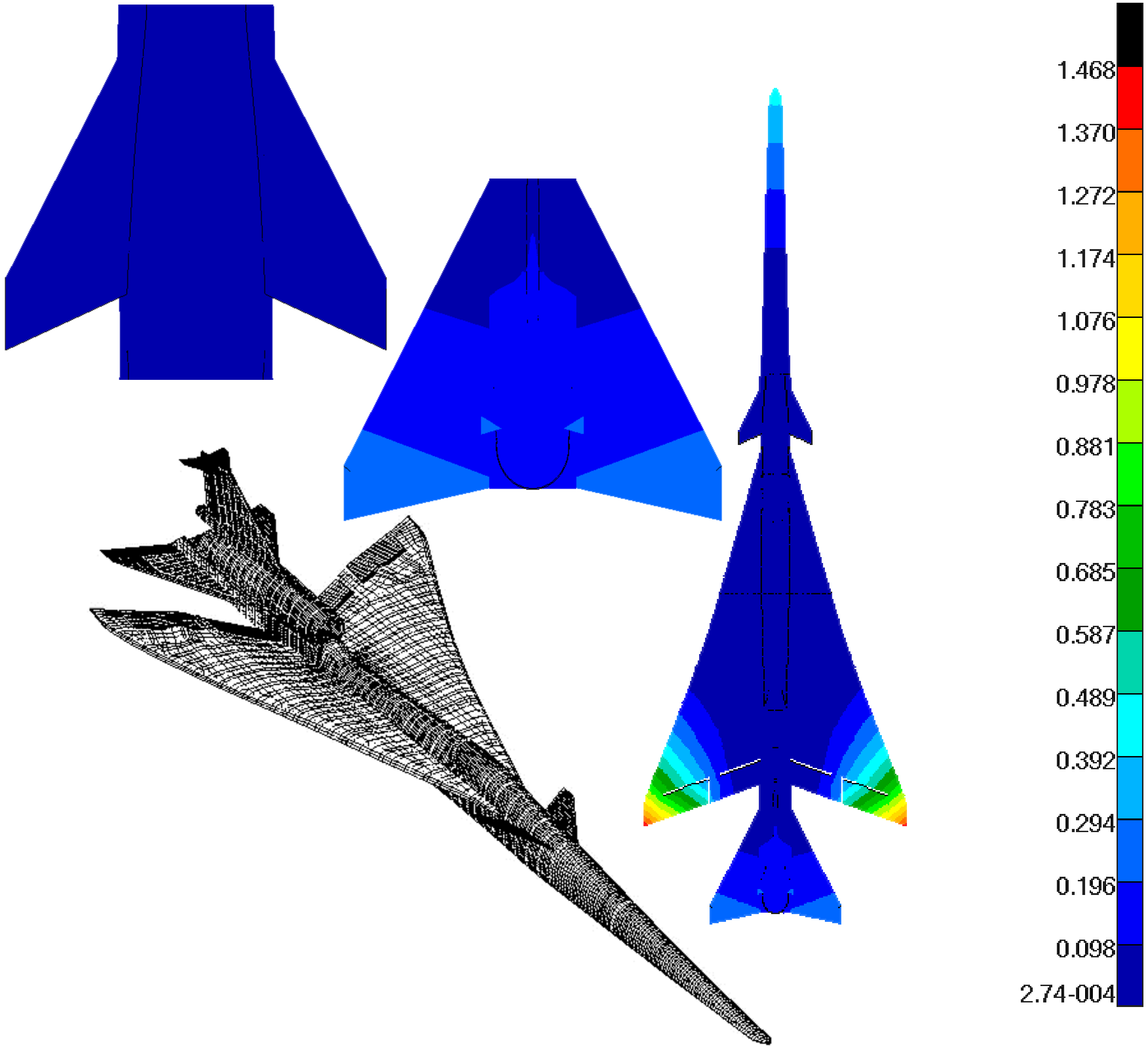
Mode	Frequency (Hz)			Notes
	Baseline	Optimum	% difference	
7	5.634			First fuselage bending
9	9.045			First wing bending + forward fuselage vertical bending + stabilator rotation
11	11.97			Forward fuselage vertical bending + first wing bending + stabilator rotation (**Asymmetric**)
15	14.76			Stabilator rotation
17	19.23			Wing tip bending + T-tail rotation + flap bending (**Asymmetric**)
19	20.08			T-tail rotation (**Asymmetric**)
20	20.54			Wing tip bending + T-tail rotation + aileron rotation + flap bending + forward fuselage vertical bending (**Asymmetric**)
22	21.75			Aileron rotation + flap rotation + T-tail bending + outboard wing bending torsion
23	22.16			Flap rotation + aileron rotation + wing tip bending + T-tail bending (**Asymmetric**)
25	22.70			Flap rotation + aileron rotation + T-tail bending (**Asymmetric**)
37	30.79			Canard bending
48	42.96			T-tail bending (**Asymmetric**)

Mode 7: 5.634 Hz



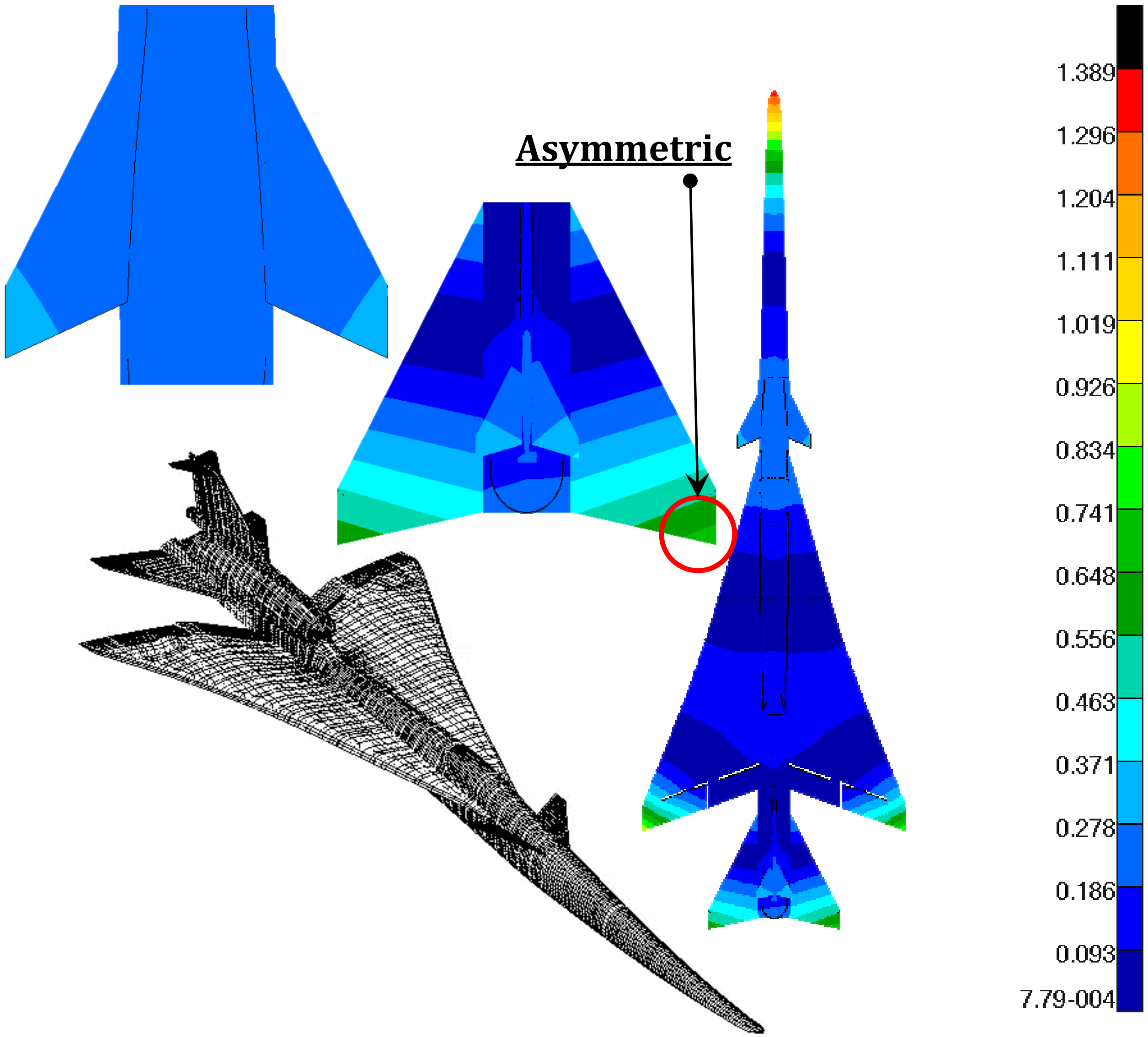
first fuselage vertical bending

Mode 9: 9.045 Hz



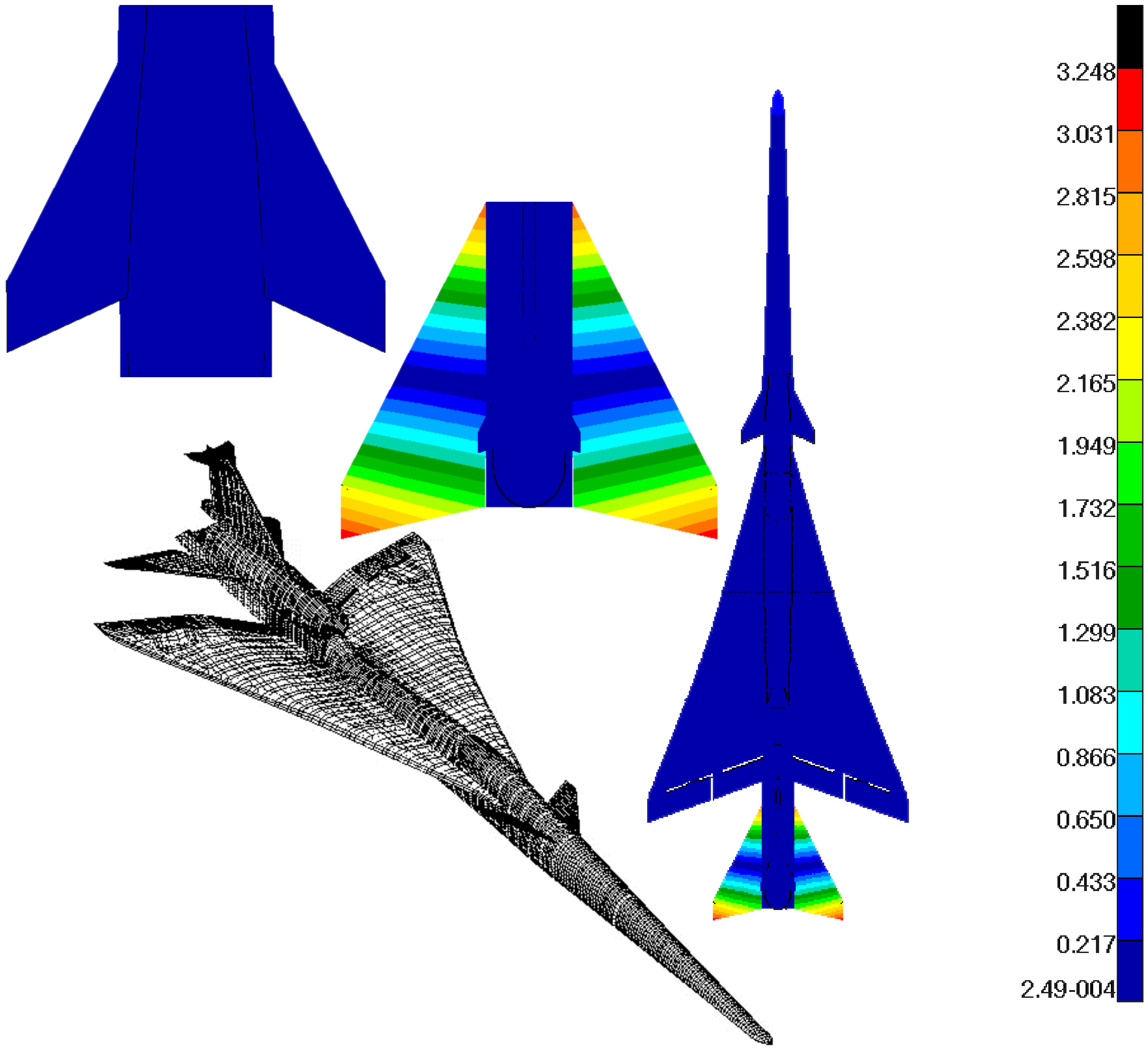
Symmetric first wing bending + forward fuselage vertical bending + horizontal tail rotation (in-phase: forward fuselage & wing)(out-phase: wing and horizontal tail)

Mode 11: 11.97 Hz



Symmetric first wing bending + forward fuselage vertical bending + horizontal tail rotation (out-phase: forward fuselage & wing)(in-phase: wing and horizontal tail)

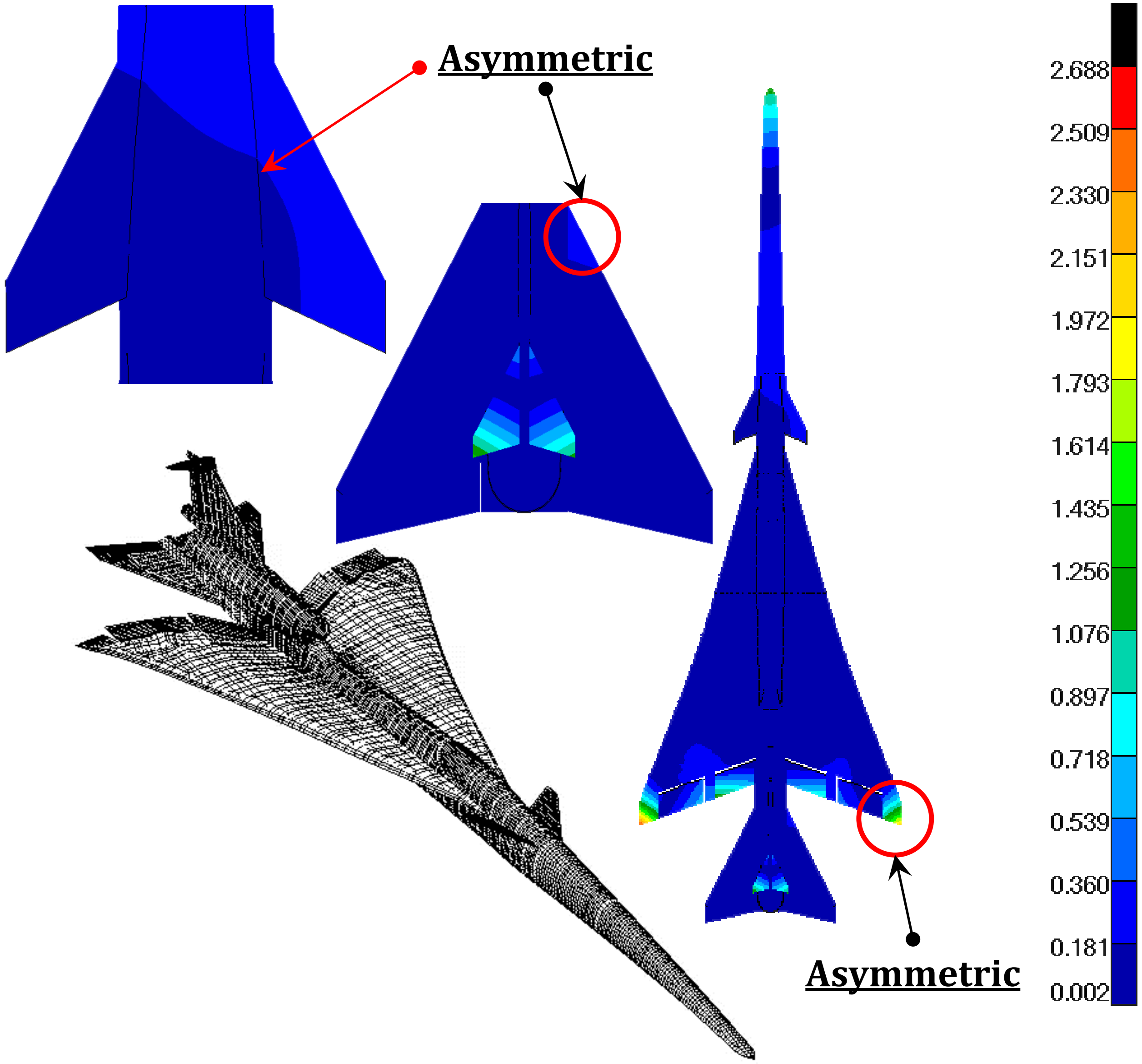
Mode 15: 14.76 Hz



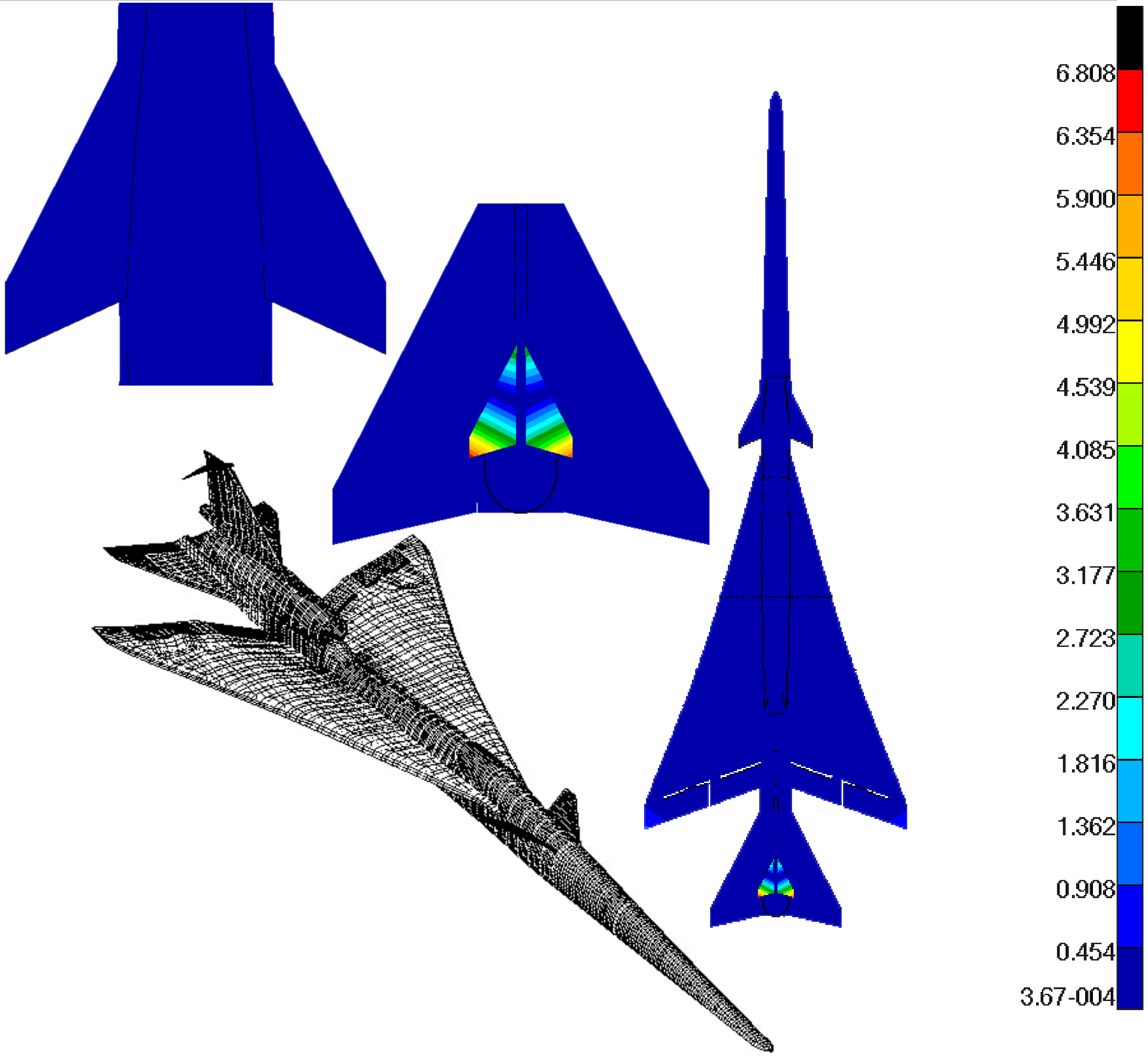
Symmetric horizontal tail rotation

Mode 17: 19.23 Hz

Mode 19: 20.08 Hz



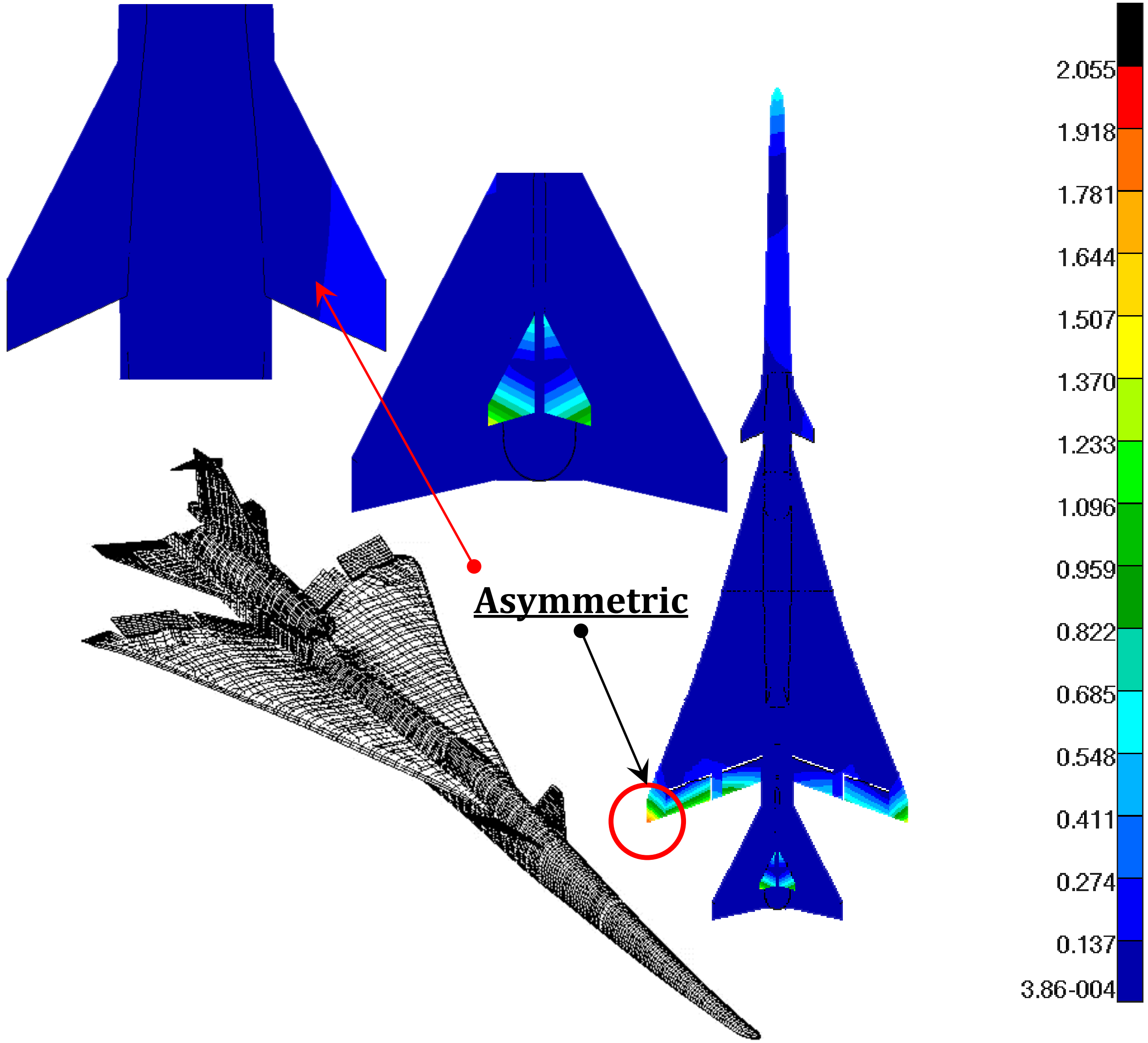
symmetric wing tip bending+Ttail rotation + flap



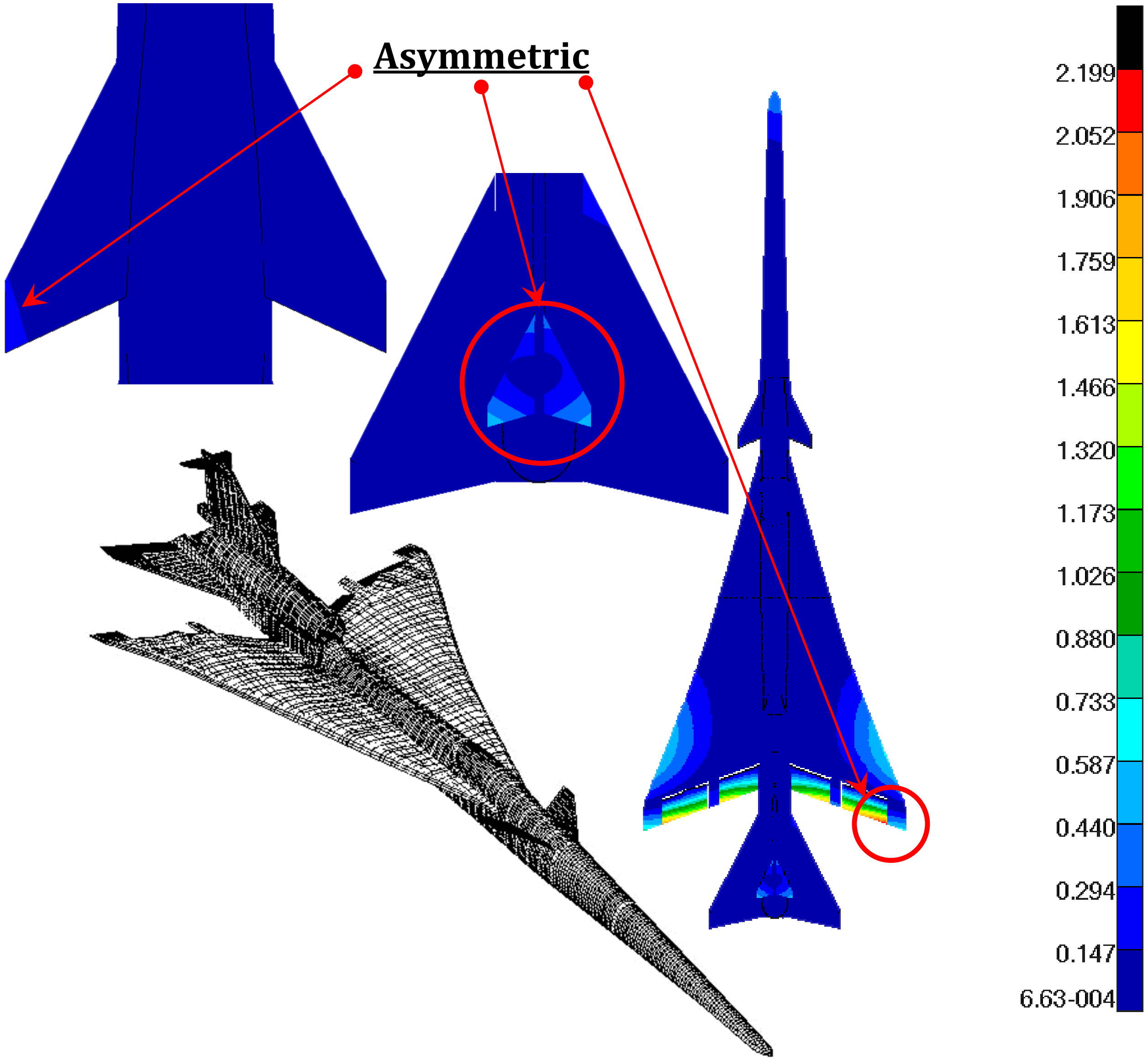
symmetric ttail rotation

Mode 20: 20.54 Hz

Mode 22: 21.75 Hz

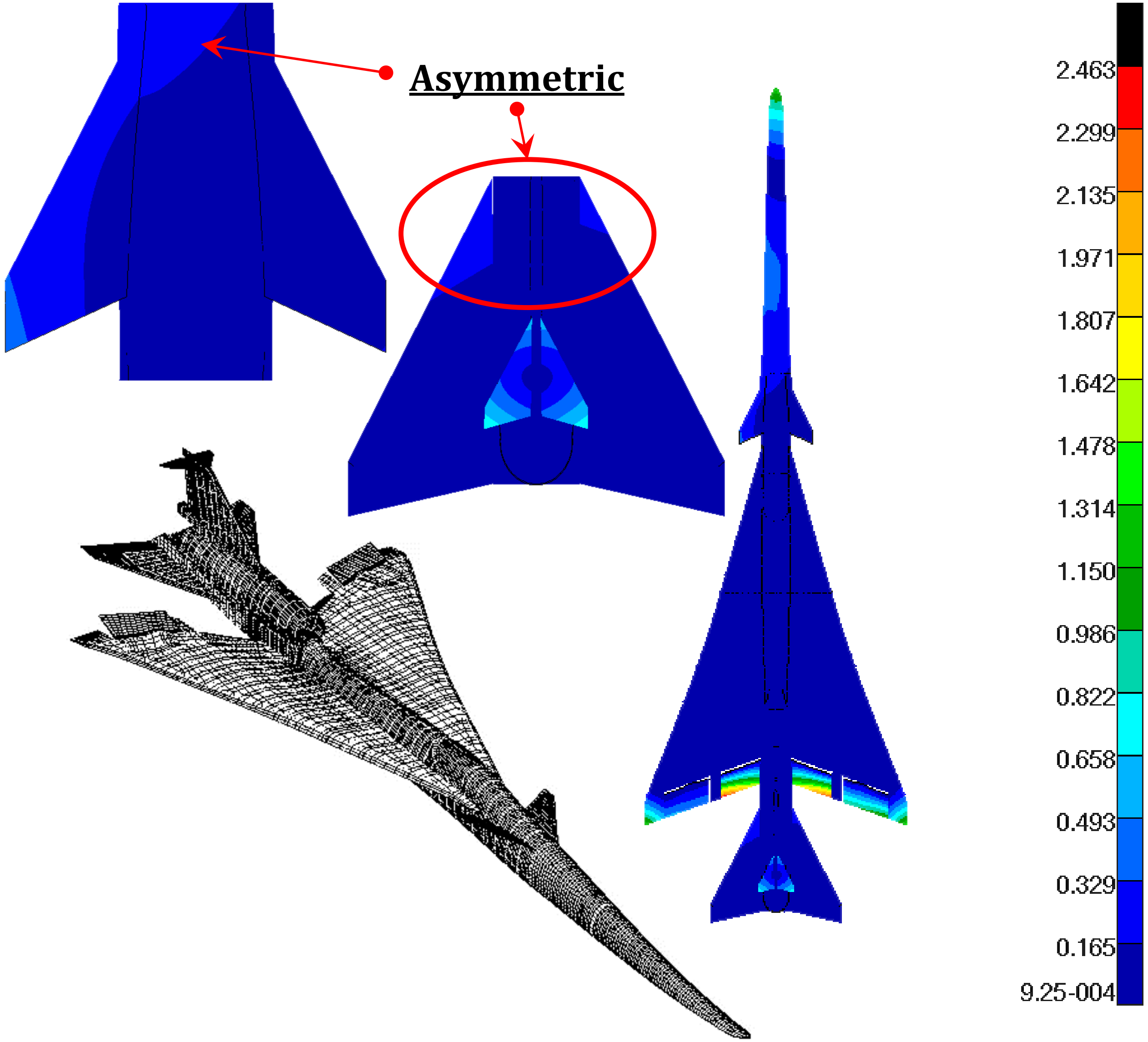


symmetric wing tip bending + ttail rotation flap & airleron rotation + forward fuselage bending + nose landing gear vertical bending (out-phase wing tip & forward fuselage) (out phase wing tip & ttail)



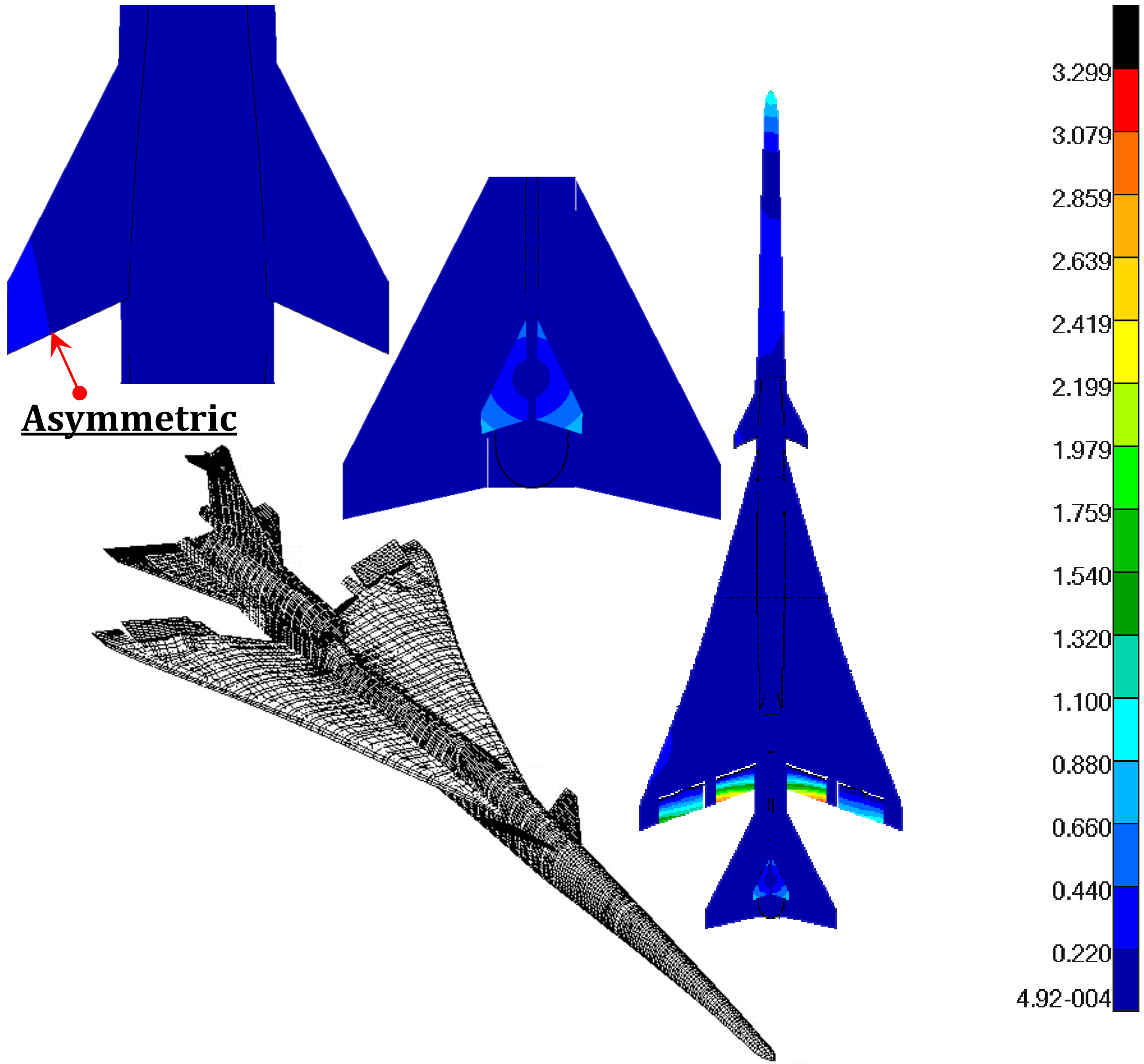
symmetric airleron + flaperon (in-phase)+ttail(pitch +yaw)

Mode 23: 22.16 Hz



symmetric Flaperon+airleron (out-phase) +ttail(pitch+yaw) +forward fulage and airleron(in-phase)

Mode 25: 22.70 Hz

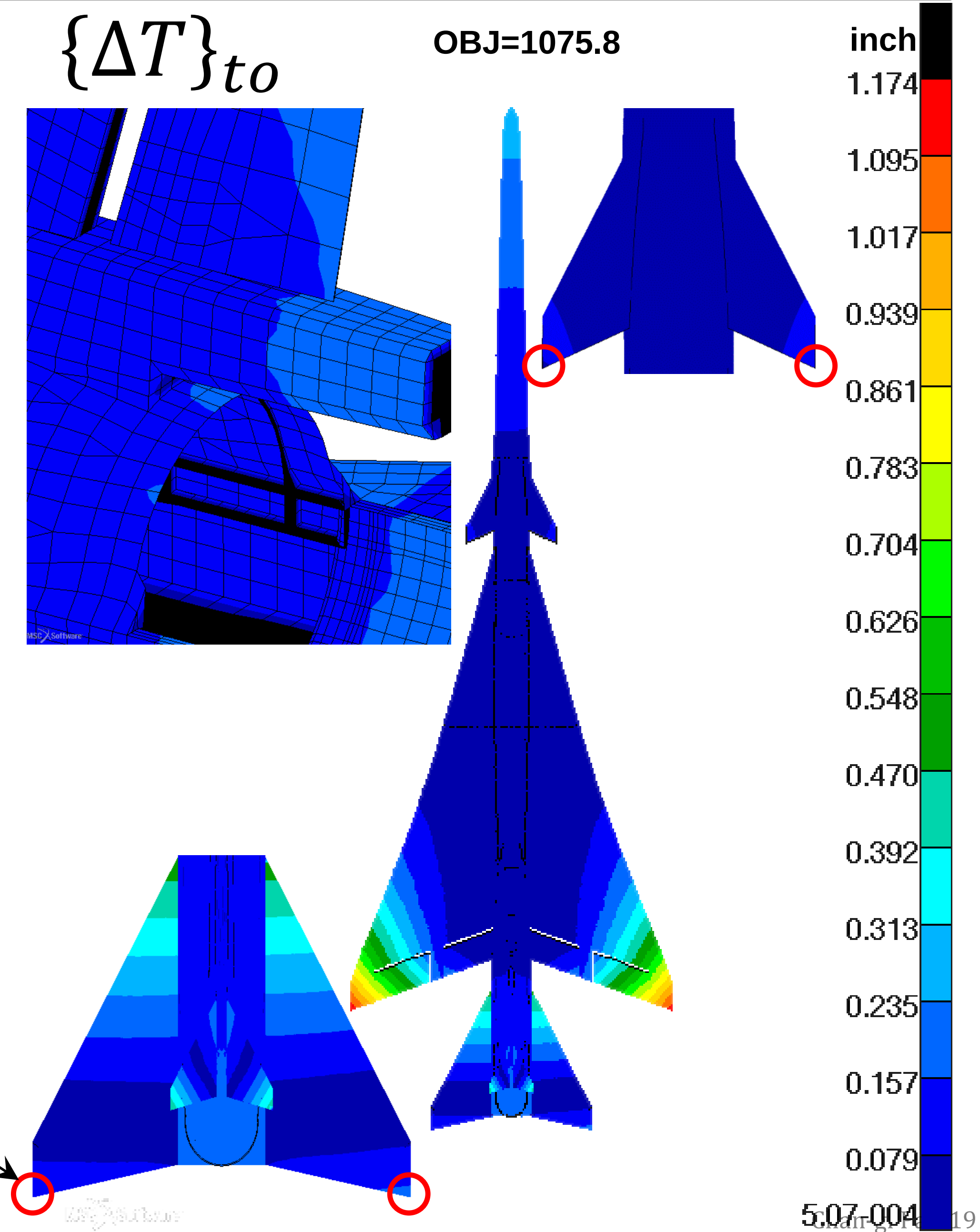


symmetric flaperon+airleron (out-phase)+ttail(pitch+yaw) + forward fulage and airleron(out-phase)

Trim Shape Difference (Baseline Configuration)

- ❑ Weight:
  - ❖ Cruise = 18499.99 lbf
- ❑ Forward CG location
  - ❖ x=836.09 inch, **y=-0.1897 inch**, z=100.68 inch
- ❑ Mach: 1.42
- ❑ Altitude: 55000 ft
- ❑ Aileron deflection angle: 0.5 deg
- ❑ T-tail deflection angle: 6.47 deg
- ❑ $\{\Delta T\}_{to} \equiv \{T\}_t - \{T\}_o$
  - ❖ $\{T\}_t$= target trim shape at surface GRIDs
  - ❖ $\{T\}_o$= trim shape based on optimum jig shape
    - ✓ $\{jig\}_o \equiv \{jig\}_b + [\boldsymbol{\Phi}]\{X\}_o$
    - ✓ $\{jig\}_o \xRightarrow[trim\ analysis]{} \{T\}_o$

X_i	Value
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.0
7	0.0
8	0.0
9	0.0
10	0.0
11	0.0
12	0.0
13	0.0



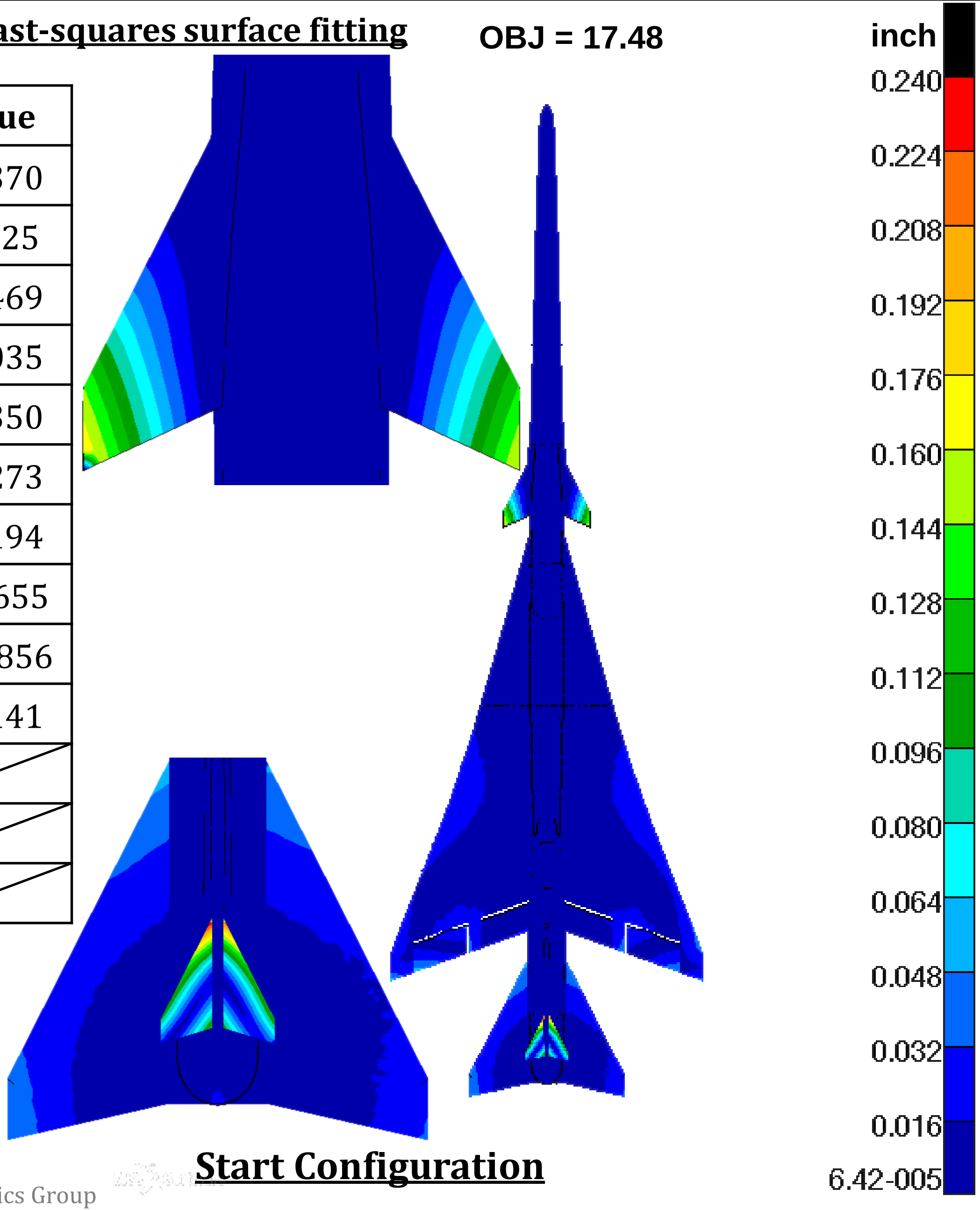
Asymmetric

Optimization #1: $\{\Delta T\}_{to} = \{T\}_t - \{T\}_o$

<u>**Use least-squares surface fitting**</u>

OBJ = 17.48

X_i	Value
1	0.4370
2	-1.125
3	0.2469
4	0.4035
5	.02350
6	0.6273
7	.04194
8	-.02655
9	.000856
10	0.1141
11	
12	
13	

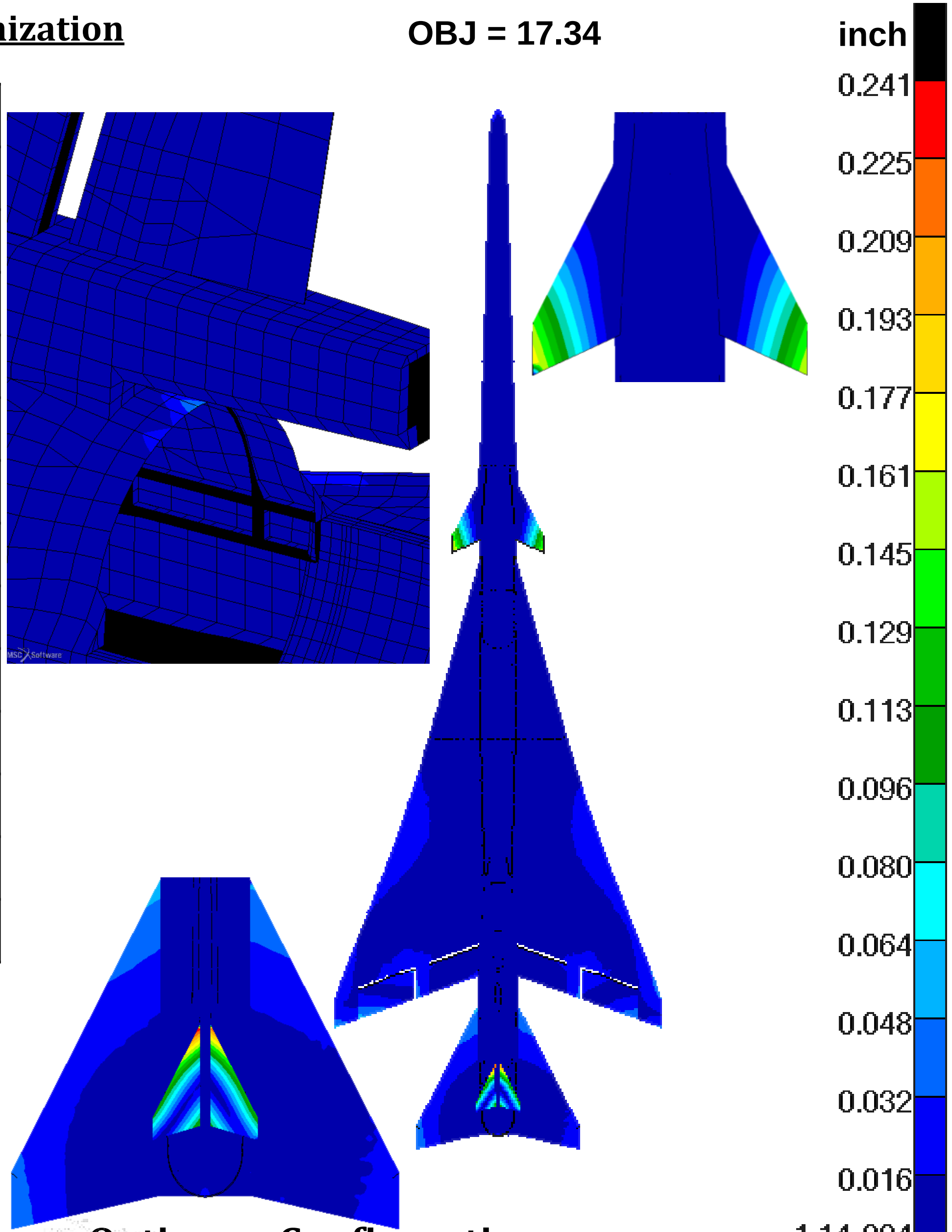


<u>**Start Configuration**</u>

<u>**Use Optimization**</u>

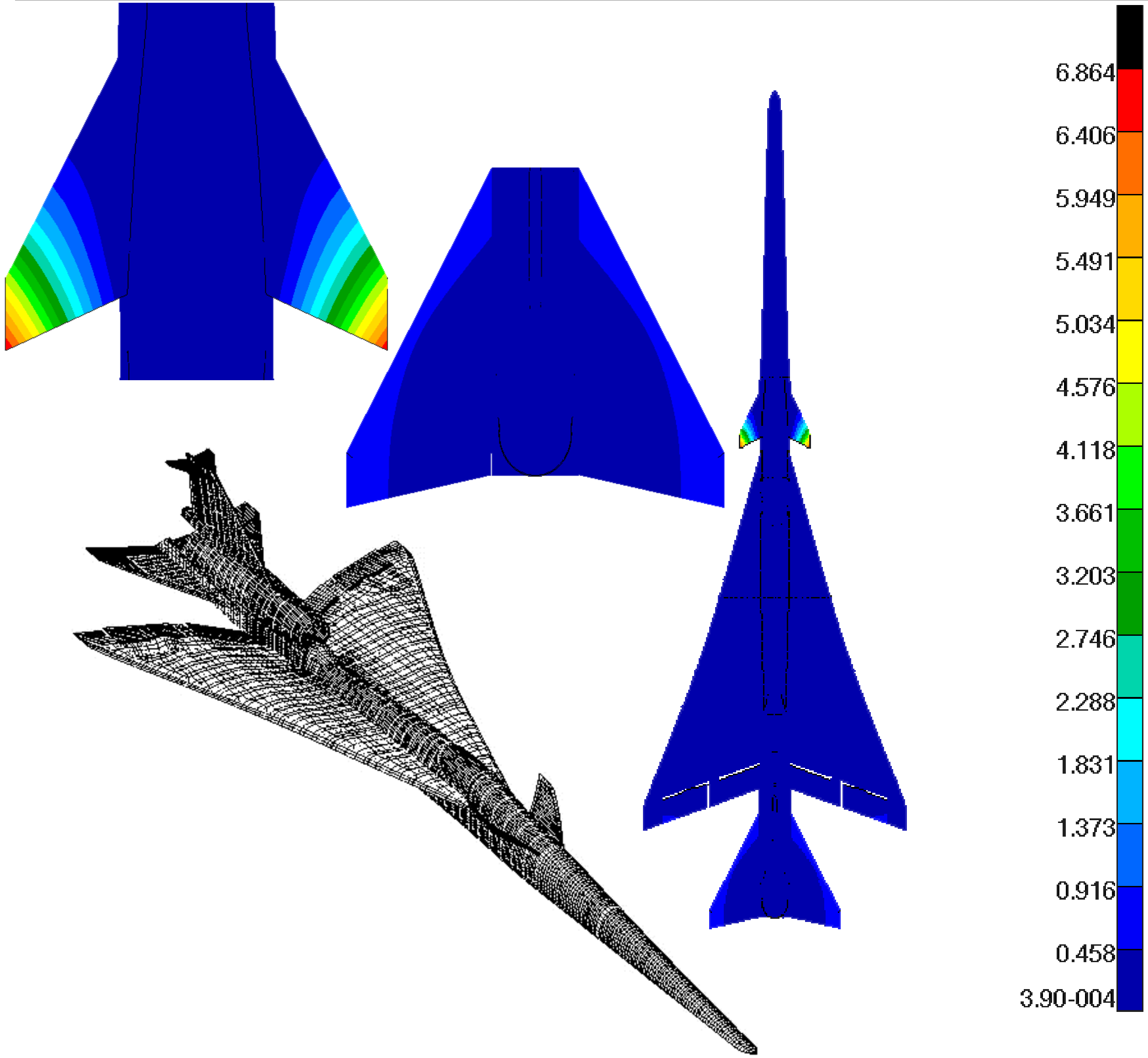
OBJ = 17.34

X_i	Value
1	0.4366
2	-1.126
3	0.2467
4	0.4031
5	.02364
6	0.6272
7	.04203
8	-.02643
9	.000992
10	0.1142
11	
12	
13	



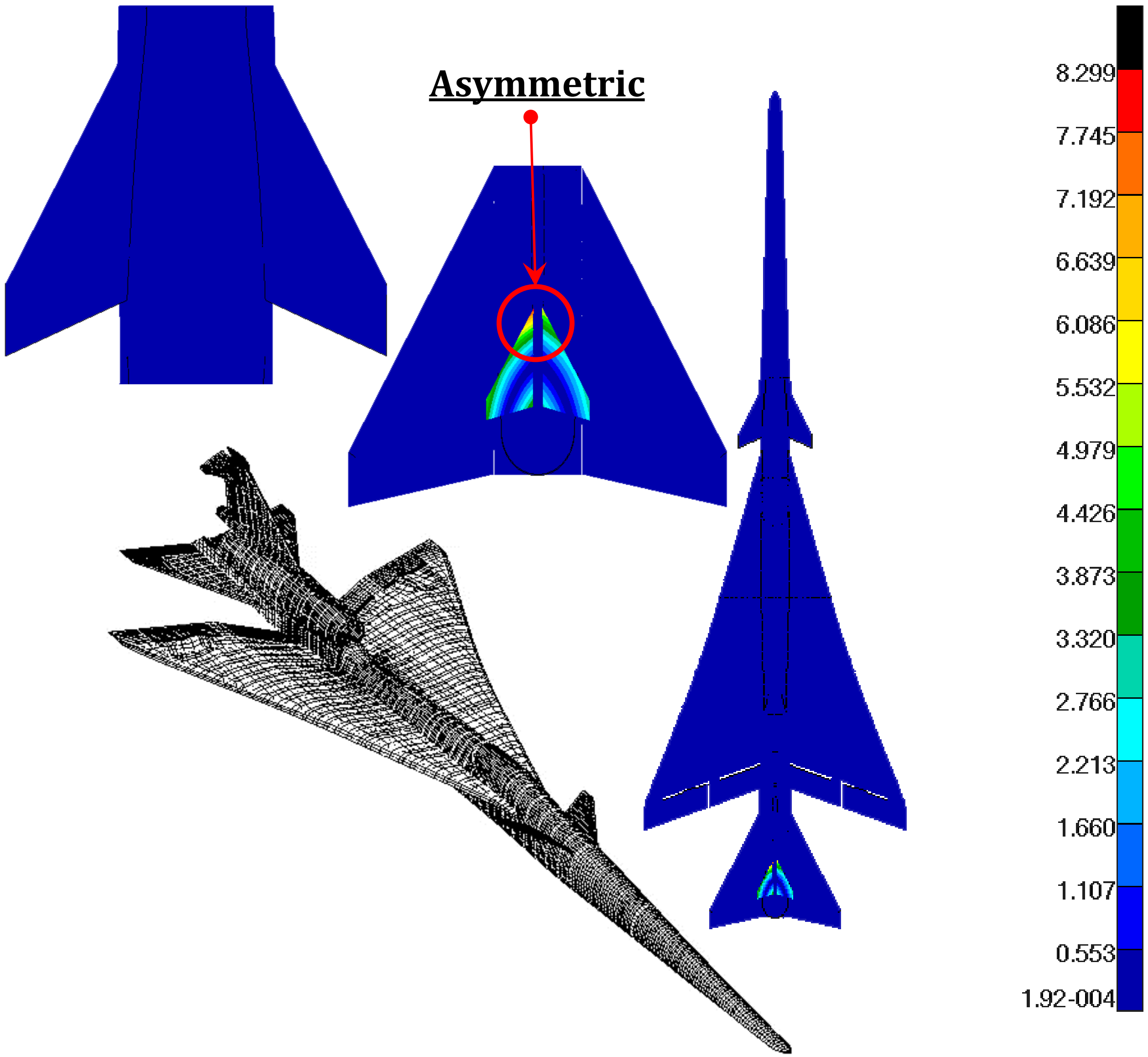
<u>**Optimum Configuration**</u>

Mode 37: 30.79 Hz



symmetric canard bending

Mode 48: 42.96 Hz



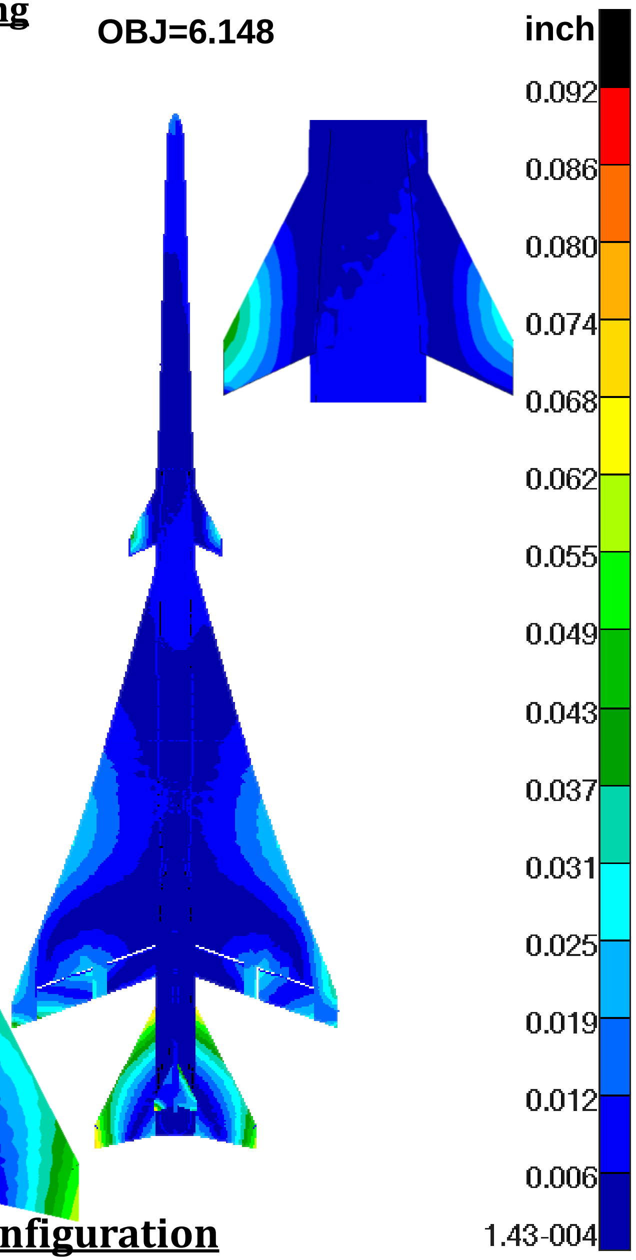
symmetric ttail

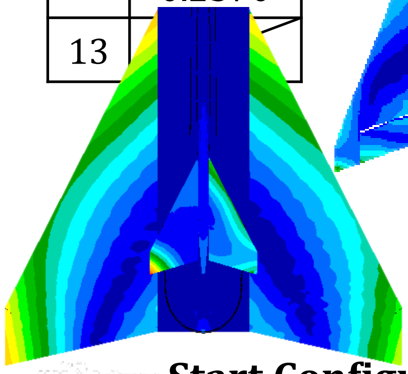
Optimization #2: $\{\Delta T\}_{to} = \{T\}_t - \{T\}_o$

Use least-squares surface fitting

X_i	Value
1	0.4366
2	-1.126
3	0.2467
4	0.4031
5	.02364
6	0.6272
7	.04203
8	-.02643
9	.000992
10	0.1142
11	
12	
13	

X_i	Value
1	0.4366
2	-1.126
3	0.2467
4	0.4031
5	.02364
6	0.6272
7	.04203
8	-.02643
9	.000992
10	0.1142
11	-0.1470
12	0.2570
13	

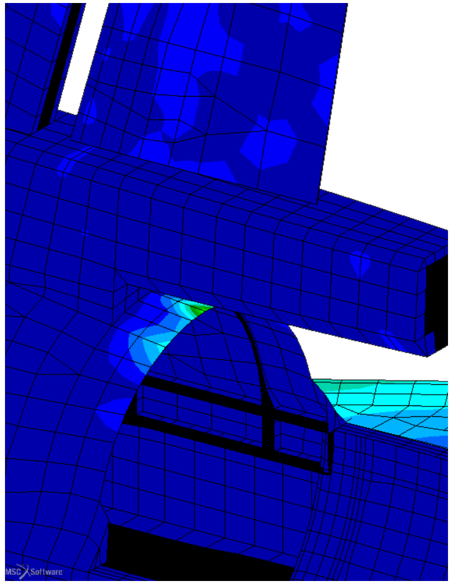




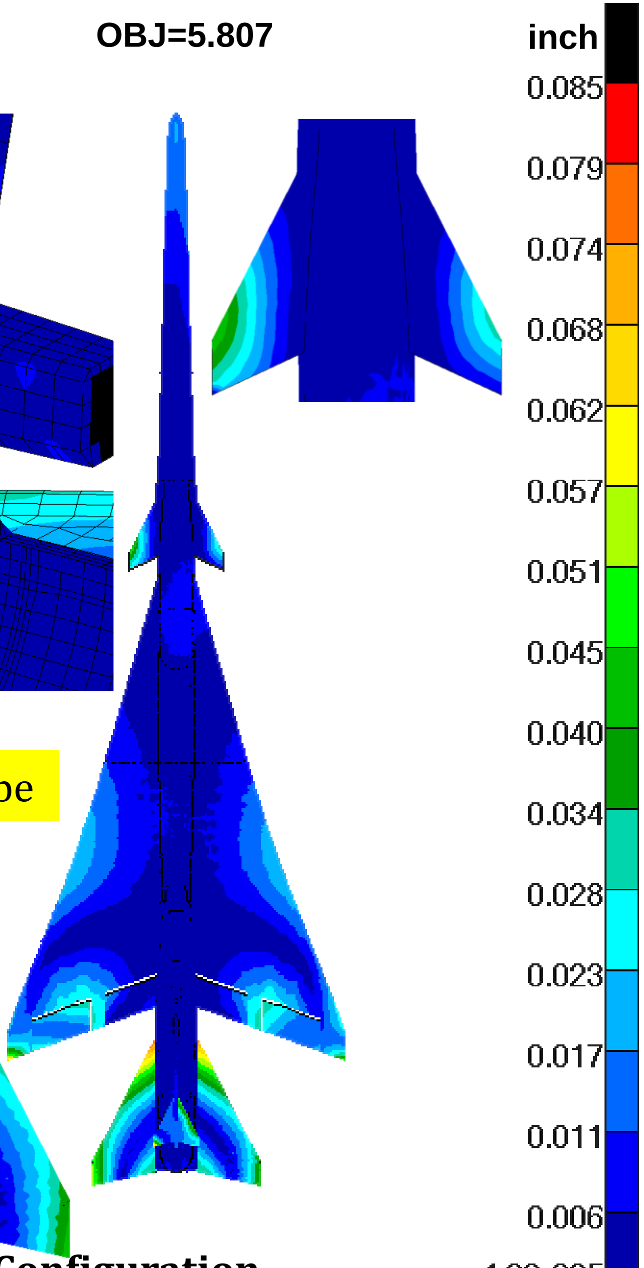
Start Configuration

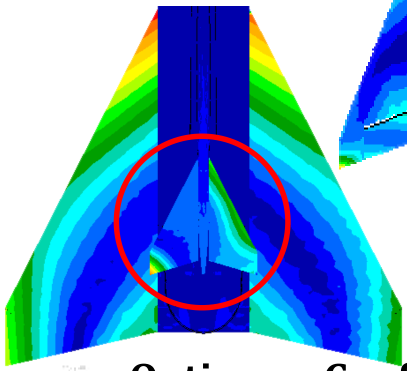
Use Optimization

X_i	Value
1	0.4370
2	-1.152
3	0.2356
4	0.3962
5	.01778
6	0.6228
7	.04228
8	-.02570
9	-.000747
10	0.1161
11	-0.1477
12	0.2575
13	



Residual shape





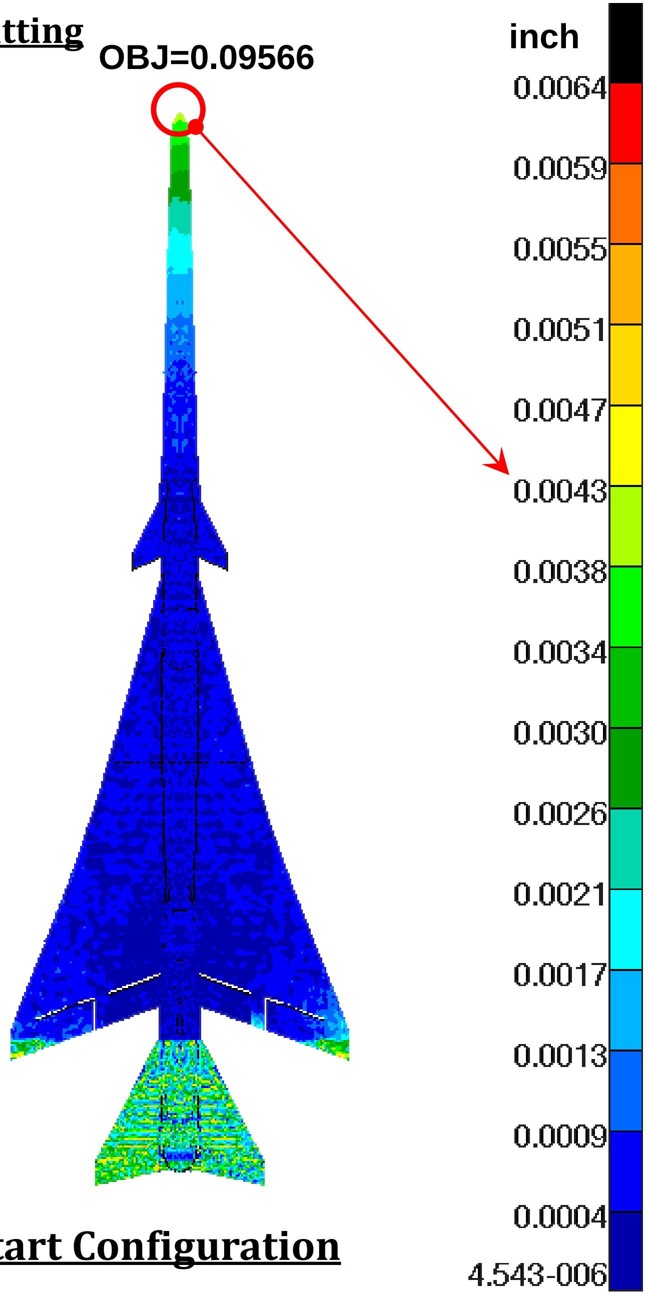
Optimum Configuration

Optimization #3: $\{\Delta T\}_{to} = \{T\}_t - \{T\}_o$

Use least-squares surface fitting

X_i	Value
1	0.4338
2	-1.152
3	0.2354
4	0.3961
5	.01920
6	0.6221
7	.04123
8	-.0265
9	-.000167
10	0.1165
11	-0.1475
12	0.2567
13	0.08358

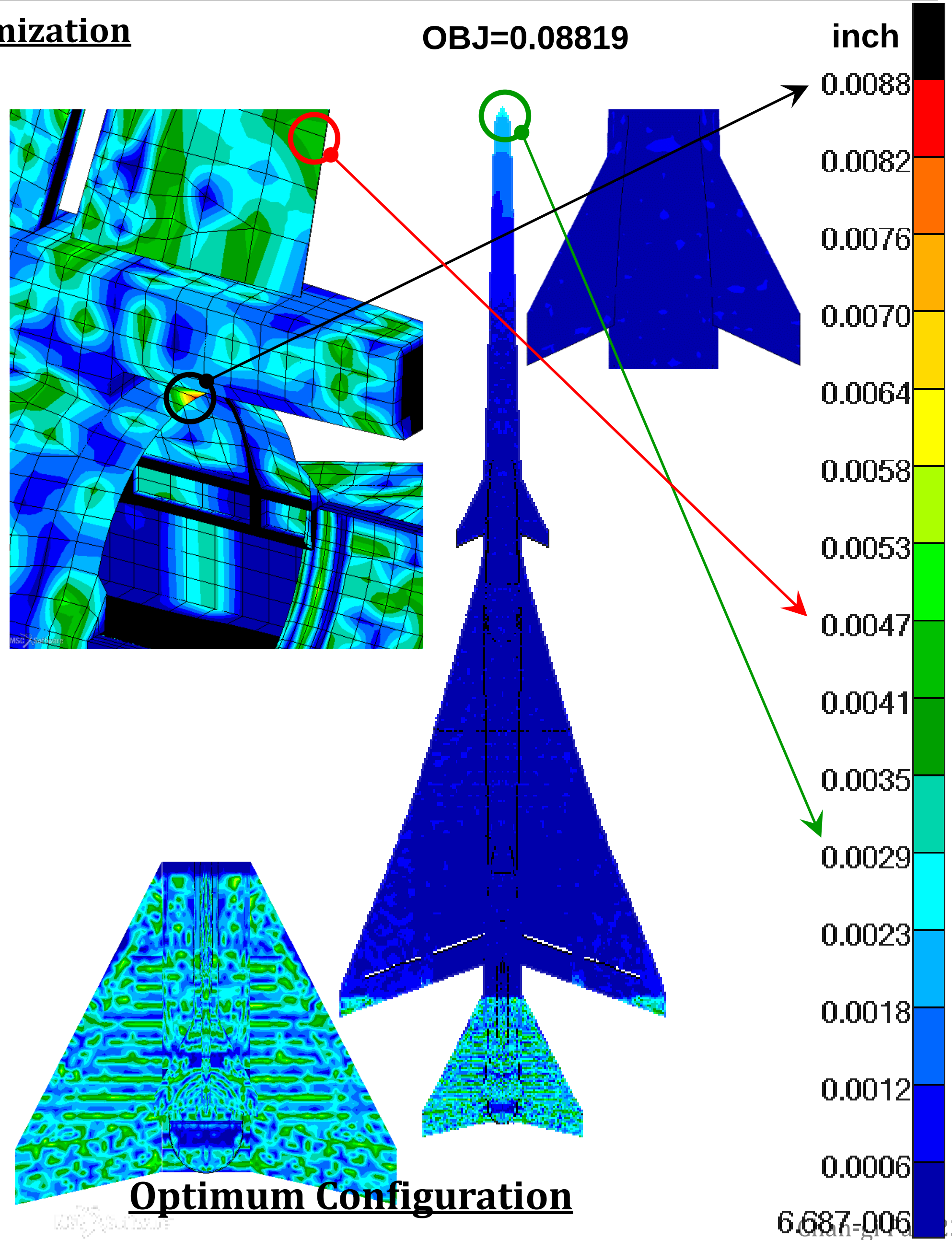
0.085 inch



Start Configuration

Use Optimization

X_i	Value
1	0.4336
2	-1.153
3	0.2353
4	0.3959
5	.01919
6	0.6220
7	.04120
8	-.0265
9	-.000292
10	0.1165
11	-0.1476
12	0.2567
13	0.08350

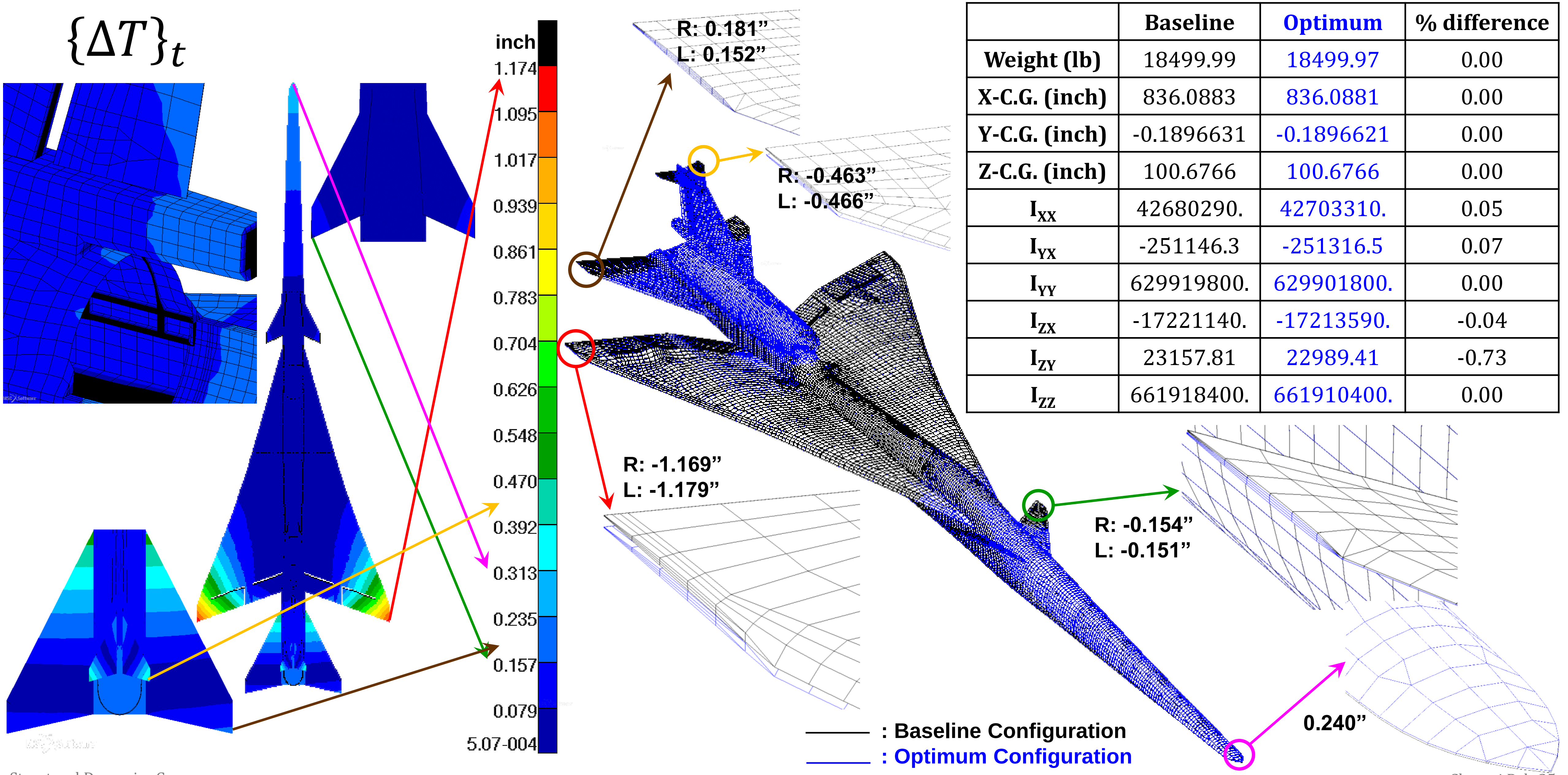


Optimum Configuration

Optimization Results

DESVAR ID	Baseline	Optimization #1		Optimization #2		Optimization #3		Comments
		Start	Optimum	Start	Optimum	Start	Optimum	
1	0.0	0.4370	0.4366	0.4366	0.4370	0.4338	0.4336	Mode 7
2	0.0	-1.125	-1.126	-1.126	-1.152	-1.152	-1.153	Mode 9
3	0.0	0.2469	0.2467	0.2467	0.2356	0.2354	0.2353	Mode 11
4	0.0	0.4035	0.4031	0.4031	0.3962	0.3961	0.3959	Mode 15
5	0.0	.02350	.02364	.02364	.01778	.01920	.01919	Mode 17
6	0.0	0.6273	0.6272	0.6272	0.6228	0.6221	0.6220	Mode 19
7	0.0	.04194	.04203	.04203	.04228	.04123	.04120	Mode 20
8	0.0	-.02655	-.02643	-.02643	-.02570	-.0265	-.0265	Mode 22
9	0.0	.000856	.000992	.000992	-.000747	-.000167	-.000292	Mode 23
10	0.0	0.1141	0.1142	0.1142	0.1161	0.1165	0.1165	Mode 25
11	0.0			-0.1470	-0.1477	-0.1475	-0.1476	Mode 37
12	0.0			0.2570	0.2575	0.2567	0.2567	Mode 48
13	0.0					0.08358	0.08350	Residual
Maximum Error	1.174”	0.240”	0.241”	0.092”	0.085”	0.0064”	0.0088”	
Objective Function	**1075.8**	**17.48**	**17.34**	**6.148**	**5.807**	**0.09566**	**0.08819**	

Optimum Aircraft Configuration



	Baseline	Optimum	% difference
Weight (lb)	18499.99	18499.97	0.00
X-C.G. (inch)	836.0883	836.0881	0.00
Y-C.G. (inch)	-0.1896631	-0.1896621	0.00
Z-C.G. (inch)	100.6766	100.6766	0.00
I_{XX}	42680290.	42703310.	0.05
I_{YX}	-251146.3	-251316.5	0.07
I_{YY}	629919800.	629901800.	0.00
I_{ZX}	-17221140.	-17213590.	-0.04
I_{ZY}	23157.81	22989.41	-0.73
I_{ZZ}	661918400.	661910400.	0.00

Summary of Natural Frequencies before and after optimization

Mode	Frequency (Hz)			Notes
	Baseline	Optimum	% difference	
7	5.634	5.633	-0.02	First fuselage bending
9	9.045	9.034	-0.12	First wing bending + forward fuselage vertical bending + stabilator rotation
11	11.97	11.97	0.00	Forward fuselage vertical bending + first wing bending + stabilator rotation (**Asymmetric**)
15	14.76	14.76	0.00	Stabilator rotation
17	19.23	19.23	0.00	Wing tip bending + T-tail rotation + flap bending (**Asymmetric**)
19	20.08	20.08	0.00	T-tail rotation (**Asymmetric**)
20	20.54	20.55	0.05	Wing tip bending + T-tail rotation + aileron rotation + flap bending + forward fuselage vertical bending (**Asymmetric**)
22	21.75	21.76	0.05	Aileron rotation + flap rotation + T-tail bending + outboard wing bending torsion
23	22.16	22.17	0.05	Flap rotation + aileron rotation + wing tip bending + T-tail bending (**Asymmetric**)
25	22.70	22.70	0.00	Flap rotation + aileron rotation + T-tail bending (**Asymmetric**)
37	30.79	30.76	-0.10	Canard bending
48	42.96	42.97	0.02	T-tail bending (**Asymmetric**)

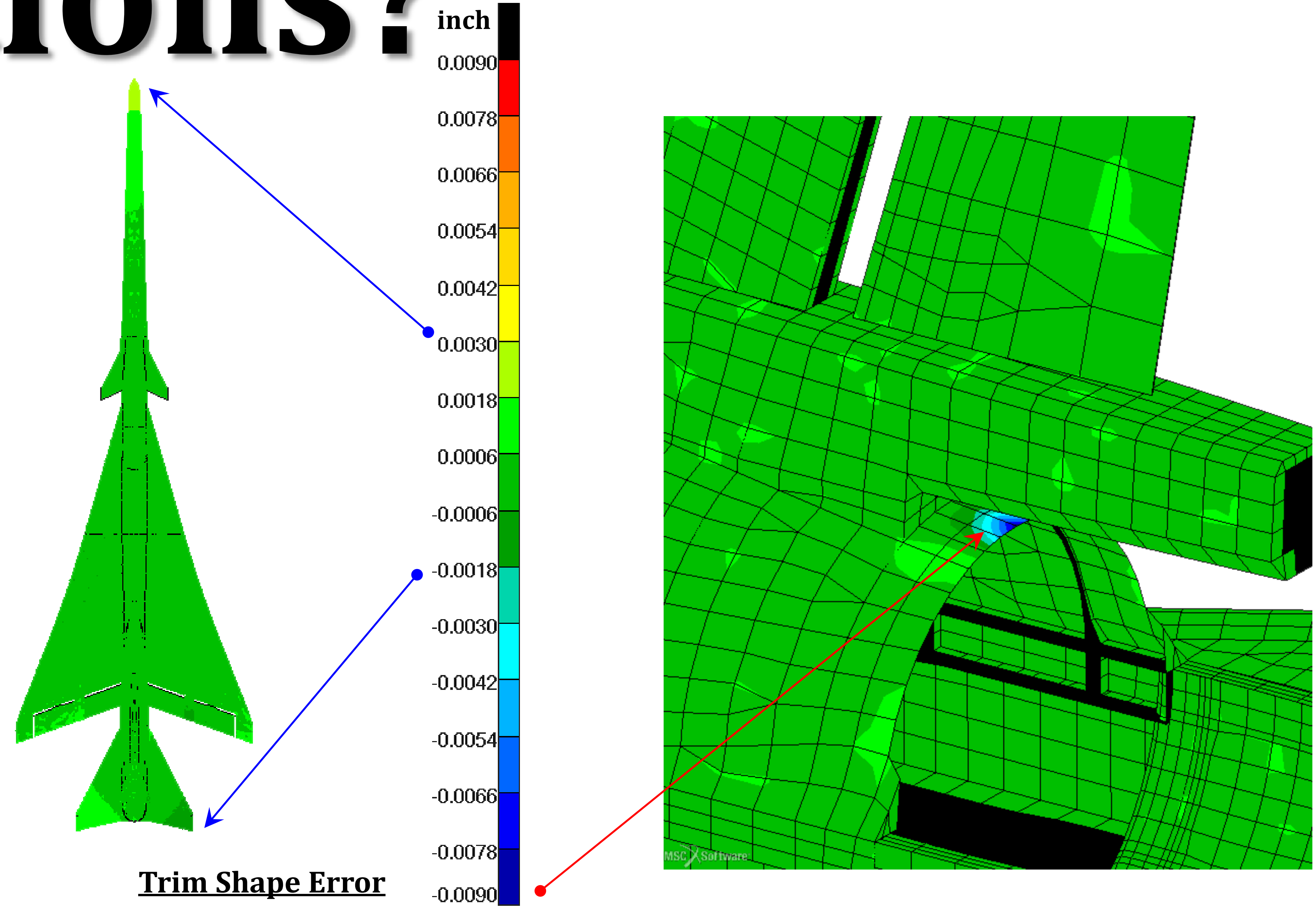
Conclusion

- In this study, the jig-shape optimization is performed using the two step approach.
  - The first step is computing the starting design variables using the **least squares surface fitting technique**.
  - The next step is the fine tune of the jig-shape using the **numerical optimization procedure**.
  - Assume **unconstrained** optimization
    - The maximum frequency change due to the jig-shape optimization is less than 0.12%.
    - The minor changes in mass moment of inertia are observed. (mostly less than 0.07%; maximum 0.73%)

- Thirteen basis function are used in this jig-shape optimization study.
  - Total of **twelve symmetric mode shapes** of the cruise weight configuration. (Asymmetric shapes exist)
  - **A residual shape** is also selected as a basis function.

- The maximum trim shape error of **1.174”** at the starting configuration becomes **0.0088”** at the end of the third optimization run.

Questions?



Trim Shape Error